Water Resources Report No. 55

The Hydrology of Maramec Spring

MISSOURI DEPARTMENT OF NATURAL RESOURCES
Division of Geology and Land Survey

Front Cover:

Young people enjoy an outing at Maramec Spring, circa 1903. From left to right: Lena Gorman, Austin Gunter, Laura Morrison, Ethel Worth and Elsie Pinto. Photo courtesy of the Lucy Wortham James Memorial Library and the James Foundation. Photographer unknown.

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THE HYDROLOGY OF MARAMEC SPRING

by

James E. Vandike

1996

MISSOURI DEPARTMENT OF NATURAL RESOURCES
Division of Geology and Land Survey
P.O. Box 250, Rolla, MO 65402-0250
(573) 368-2100

Library of Congress Catalog Card Number: 96-80370
Missouri Classification Number: MO/NR. Ge 9:55

Vandike, James E., 1996, ***The Hydrology of Maramec Spring,*** Missouri Department of Natural Resources, Division of Geology and Land Survey, Water Resources Report Number 55, 104 p., 33 figs., 8 tbls., 1 app.

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ABSTRACT

A karst drainage system developed in Lower Ordovician-age dolomites and sandstones in Phelps and Dent counties, Missouri, provides recharge to Maramec Spring, Missouri's fifth largest spring. The outlet of Maramec Spring is a cave opening developed in the Lower Gasconade Dolomite, but divers have shown that the conduit which channels water to the spring extends downward into the upper Eminence Dolomite of upper Cambrian age, and reaches depths of at least 190 feet below pool elevation. The discharge of Maramec Spring varies from a low of about 56 ft^3/sec to more than 1,100 ft^3/sec, and averages about 155 ft^3/sec. It flows into the Meramec River one-half mile north of the spring where it more than doubles the flow of the river most of the time.

Dye tracing shows that Maramec Spring is recharged from a 310 mi^2 area west and south of the spring in Dry Fork, Norman Creek, and Asher Hollow watersheds. All of these watersheds are drained by losing streams that channel a significant part of their runoff into the subsurface. A 12 mi^2 area of Asher Hollow is estimated to provide between 5.1 and 6.3 percent of the recharge for Maramec Spring. Norman Creek, which likely has the highest groundwater recharge rate of the three drainages, provides between 22.2 and 27 percent of Maramec Spring recharge from its 52 mi^2 drainage area. With the exception of a small area in the upper watershed, Norman Creek is a losing stream throughout its length. Dry Fork, the largest tributary of the upper Meramec River, drains a total of 383 mi^2. The 246 mi^2 area draining into Dry Fork upstream from Phelps County Route F provides recharge to Maramec Spring. Dry Fork is thought to provide between 66.7 and 72.2 percent of the springs recharge. Asher Hollow and Norman Creek seldom carry surface flow throughout their lengths, but even the losing reaches of Dry Fork will typically contain surface flow during wet weather, indicating that it has a lesser recharge rate than the other drainages.

Hourly rainfall data collected at four locations in Dry Fork watershed, combined with hourly discharge and specific conductance data collected at Maramec Spring, shows that discharge at the spring begins to increase as little as 4 to 6 hours after precipitation begins. The response time appears to be greater during relatively dry weather, and less during wet weather when antecedent soil moisture is high. The rapid increase in Maramec Spring discharge is due to an increase in pressure head in the karst system as the water-table elevation is increased in the recharge area. The actual water supplied by the recharge does not begin to arrive at the spring for several days, and the mass center of the recharge typically reaches the spring 12 to 15 days after heavy rainfall.

No water-quality information was collected as part of the study, but a comparison of pre-1970 data with more recent information gathered by the U.S. Geological Survey in 1993, 1994, and 1995 indicates that water quality has not changed greatly at Maramec Spring since the first data were collected in the early part of this century.

There has long been confusion about the correct spelling of the word Meramec. The current accepted spelling of the river is M<u>e</u>r<u>a</u>mec while that of the spring is M<u>a</u>r<u>a</u>mec. Cook's spelling, Me<u>rri</u>mac, appeared on his 1823 plat map, field notebooks and other early maps. Maps made after about 1860 typically show today's spelling for the spring and river.

INTRODUCTION

(Excerpts adapted from the notebooks of Nathanial Cook, 1823)
35.00 Merrimac 200 links (6.50 chains below the entrance of Big Spring branch; 150 links Big Spring SW 25.00 chains)
45.00 Bed of bright iron ore, 800 links wide

In 1823, surveyor Nathanial Cook penned into his notebook what may have been the first written description of Maramec Spring while surveying in Section 1, Township 37 North, Range 6 West of the 5th Principal Meridian, a section of land that would become part of Phelps County, Missouri, 34 years later. It is not possible to know the surveyor's impressions upon first seeing the spring, but other, more inspiring words quite likely came to him. History should not judge Cook too harshly for his lack of description and inspirational prose because surveyors under contract to the United States General Land Office at that time were paid for their surveying, not literary skills, and they earned only three dollars per mile. Field notes required paper, ink, and time, all of which were expensive commodities in the early 1800s. Notes were kept to a bare minimum; they described distances in chains and links (1 chain is 66 ft, 1 link is .66 ft or about 8 inches) and bearings, and their field notes

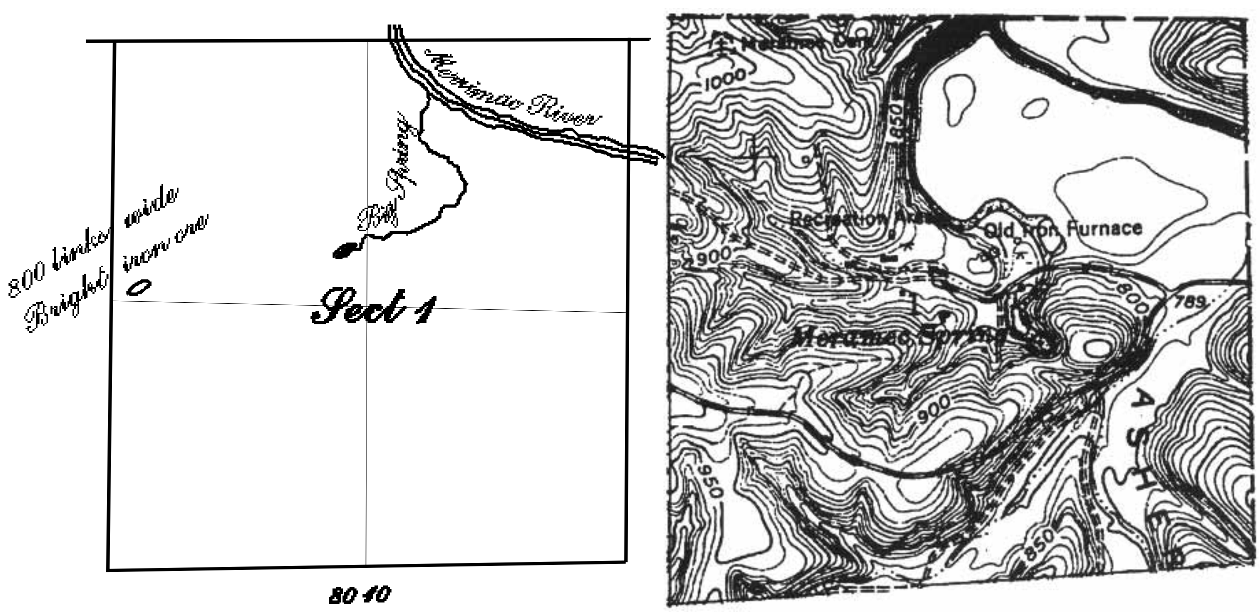


Figure 1. Artist interpretation of Cook's 1823 plat map of Sec. 1, T. 37 N., R. 6 W. next to a modern U.S.G.S. 7.5 minute topographic map of the same section.

contained only the most meager descriptions of land, mineral, and timber resources.

Although sparse with words, Cook's brief description of Missouri's fifth largest spring and the surrounding area listed all of the ingredients necessary for manufacturing a product that was often scarce on the expanding western frontier...iron. Using the technology of the day, iron was smelted by layering charcoal, limestone, and iron ore in a fire-brick lined sandstone smelting furnace. The charcoal fueled the fire necessary to melt the iron ore. Limestone served as a flux, which kept most of the impurities separated from the molten iron. Large volumes of low-pressure compressed air were forced upward through the furnace to bring the temperature to and beyond the melting point of iron. Nathanial Cook's field notes and plat map listed these ingredients: a deposit of iron ore a half mile west of the spring, abundant local timber for making charcoal, and a giant spring to power the air compressors, trip hammers, and other tools of the ironworks. The limestone (actually dolomite, a magnesium-rich limestone) was locally abundant, as was the sandstone for making the iron furnace exterior.

Five hundred miles to the east in Ohio, iron monger Thomas James was operating a successful iron smelter. How James learned of Maramec Spring and the neighboring iron deposit 85 miles southeast of St. Louis is not entirely clear. Some historians claim that Native Americans familiar with the Meramec River valley camped at James' farm while journeying to Washington, told him of the spring, and showed him the rust-red paint they made from the iron ore. A more logical, but far less interesting explanation, is that James learned of the site from business associates in St. Louis who had access to the newly acquired survey information.

Thomas James journeyed to the "Big Spring" in late 1825 or early 1826, and the following year began building the first commercially successful iron smelter west of the Mississippi River. It was destined to supply iron to St. Louis and westward for the next 50 years.

James D. Norris, 1964, in his book *Frontier Iron, The Maramec Iron Works, 1826-1876*, presents a fascinating historical account of the James Family, the Maramec Iron Works, the economics of the day, and many other facets of life in the early 19th century Missouri wilderness. What were not recorded were the thoughts of the first explorers to see the waters rising at Maramec Spring. The concerns of the day likely centered around more practical matters such as food, shelter, and survival, but one cannot help but wonder what questions came to the minds of those who first saw the spring. Actually, the early explorers first thoughts may not have been all that different from those of today's visitors. Where, they often ask, does the water come from that discharges at Maramec Spring? Is it the rising of some distant surface river that was lost underground? The early explorer likely had similar questions, but at that time, had no means to determine the answers.

When the Maramec Iron Works was in full production, the spring provided nearly all of the power that could not be supplied by the muscles of the men who labored there. James constructed several low dams eight to 10 ft high to increase the height or head potential of the water (figure 2). Water power potential depends on two factors—volume of flow and the height that the water can fall. Water discharging from a spring the size of Maramec, even with only a few feet of fall, can supply many horsepower of energy, and more than enough to run the iron works for 50 years. A large undershot water wheel powered a high-volume, low-pressure air compressor that fed the furnace fire. The same water passed through smaller wheels to power the giant trip hammers that were used to forge the impurities from the pig iron, and convert it to wrought iron. The water also powered a grist mill that ground grain for

Figure 2. This scenic waterfall at Maramec Spring was the site of an undershot water wheel that helped power the Maramec Iron Works. Photo by Jim Vandike.

the facility and area settlers, a sawmill, and drinking water to the workers and residents.

More than a century has passed since smoke belched from the inferno inside the furnace; and although one of the giant trip hammers is still in place, it thunders no more. Today, the spring has a much quieter purpose-it provides recreation for thousands of visitors each year. Some visit the spring to take advantage of the trout fishing it offers. A trout rearing facility is operated at the spring by the Missouri Department of Conservation (MDC) to supply trout for the spring branch and adjacent Meramec River. The spring also provides habitat for several unusual species of aquatic cave fauna that live within the system, but these inhabitants of the water are rarely seen by visitors. The springs water also cools and maintains the flow of the upper Meramec River, allowing it to be used by floaters during even the driest seasons.

Granted, the uses of Maramec Spring have changed over the past 160 years, but the spring is no less important to the economic well being of the area today than it was in the days of Thomas James. In fact, the protection of its water quality is even more critical today than ever in past.

Maramec Spring has been the focal point of several studies since the mid 1970s. Some were undertaken after environmental accidents, others were more academic in nature. All of them have helped to answer some of the questions concerning the recharge area of the spring and its hydrologic characteristics. In 1993, the Department of Natural Resources (DNR) and the James Foundation entered into a cooperative

agreement to study the hydrogeology of the spring system to gain further knowledge about the spring system. This study was funded, in part, by a water quality planning grant through DNR's Water Pollution Control Program. The purposes of the study were to better define the recharge area for the spring, to determine the rainfall, runoff and groundwater recharge relationships in the recharge area, and to quantify the flow and recharge characteristics of the spring. Figure 3 is a location map of the study area. It includes parts of Phelps, Dent, Crawford, Texas, and Reynolds counties, which covers an area of approximately 1,000 square miles.

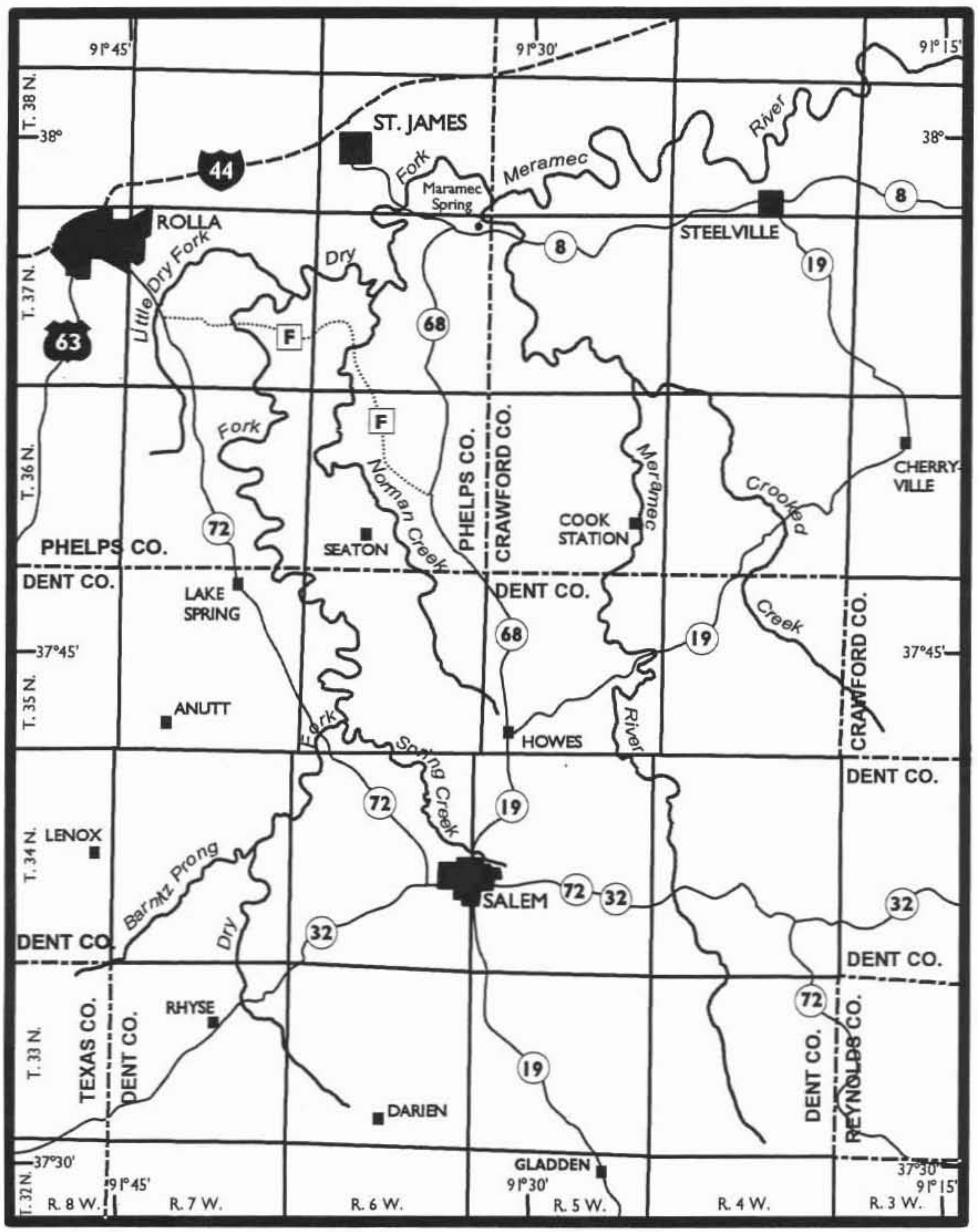


Figure 3. Location map of the Maramec Spring study area.

ACKNOWLEDGMENTS

This report bears the name of only one author, but the efforts of many people added to the success of the project. Danny Marshall, Regional Director for the James Foundation, initiated the study which lead to this report. He is deeply committed to developing a better understanding of the Maramec Spring system. His interest, support, and enthusiasm were greatly appreciated.

Land owners and residents in the study area were almost universally cooperative, allowing access to the creeks, springs and sinkholes on their land. Three precipitation stations were established in Dry Fork watershed on farms owned by Tom and Cindy Strain, Eddie Howard, and Harold and Diane Crouch. Their cooperation is sincerely appreciated.

Dr. A.C. Spreng, Geology and Geophysics Department, University of Missouri-Rolla, provided hourly precipitation and daily temperature data from the weather station operated at the University. The Salem District Office of the Mark Twain National Forest, and DNR's Montauk State Park provided weather data at the end of each month. In addition, Montauk State Park naturalist, Marian Goodding, and her staff collected specific conductance data at Montauk Spring, and regularly changed the dye monitoring packets at Montauk Spring. The National Park Service, Ozark National Scenic Riverways, cooperated by granting a special use permit to allow vehicle access and sample collection at Welch Spring.

The work performed at Maramec, Alley, and Big springs in 1985 and 1986 by Dr. Shirley J. Dreiss, University of California-Santa Cruz, helped provide a good technical base for the present project. Tragically, Dr. Dreiss died in an automobile accident in the Santa Cruz Mountains on December 14, 1993. Her untiring work and skill at deciphering karst drainage systems will be greatly missed. This report is dedicated to her memory.

The cost for much of the study was defrayed by a grant obtained through DNR's Water Pollution Control Program. The author appreciates the efforts of Ed Knight, John Madras and others in the Water Pollution Control Program for their cooperation and assistance.

H. Dwight Weaver, Divison Information officer for DNR's Division of Geology and Land Survey (DGLS), reviewed and edited the manuscript. Design, layout and preparation of illustrations was accomplished by Susan C. Dunn, DGLS graphics. Their talent, creativity, and professionalism are, as always, greatly appreciated.

PREVIOUS WORK

Several previous studies helped lay the foundation for the present project. Doll (1938) estimated recharge areas for most of Missouri's larger springs, including Maramec Spring. Doll predicted that Maramec Spring receives recharge from an area south and west of the spring, in Dry Fork and Normal Creek watersheds. He based this largely on the proximity of large, normally dry sections of drainages to Maramec Spring. Doll recognized that Dry Fork and many of its tributaries had flow deficiencies most of the year, and that the only times there were appreciable surface-water runoff were after heavy rainfall or during prolonged wet weather.

Williams and Martin (1963) performed a brief but valuable study in Dry Fork, Little Dry Fork, and Norman Creek watersheds. The U.S. Army Corps of Engineers had proposed constructing sizeable impoundments on each of these three streams as part of their overall Meramec River drainage project. Preliminary sites selected by the Corp on each of these streams had serious deficiencies, particularly on Dry Fork and Norman Creek. Williams and Martin showed that the proposed dam sites were within losing-stream reaches where water impounded by the structures would be lost underground, instead of remaining on the surface. Much of the time, the impoundments would likely have been little more than large mud flats. The Corps ultimately abandoned plans to construct dams on any of the three drainages.

Gann and Harvey (1975) conducted the first dye trace which linked Maramec Spring to part of its recharge source. They injected dye into the channel of Norman Creek about 8.7 miles southwest of Maramec Spring, and used a simple fluorometer to analyze grab samples and activated charcoal packets for the dye. The dye was not detected until between 68 and 75 days after injection, and was recovered only at Maramec Spring.

The second "trace," which showed a connection between recharge area and spring, occurred in November 1981. Unlike the Skelton and Harvey trace, this trace was accidental and was the result of a pipeline leak that occurred nearly 13 miles southwest of Maramec Spring, just north of where Dry Fork crosses the Dent-Phelps County line. A pipeline transporting a nitrogen-based liquid fertilizer developed a leak a few hundred feet from Dry Fork. At first thought to be a minor leak by the pipeline company, the spill proved to be much more serious. The fertilizer had a very high chemical oxygen demand and effectively depleted the dissolved oxygen from the groundwater it affected. A major fish kill resulted at Maramec Spring. The dissolved oxygen, normally more than 7 milligrams per liter (mg/L), was reduced to nearly zero for several days (Vandike, 1982). A dye trace was performed a few months after the spill and conclusively proved that the source of the elevated nitrogen and low dissolved oxygen was the fertilizer lost from the pipeline (Vandike, 1985).

Dreiss (1989a and 1989b) used data collected at three Missouri springs, including Maramec Spring, to study the changes

in water chemistry caused by storm water recharging the spring systems. In this cooperative study, DNR's Division of Geology and Land Survey collected water samples from Maramec Spring each four hours and analyzed them for calcium, magnesium, and bicarbonate. In addition, DGLS collected specific conductance and discharge data at Maramec Spring, and precipitation data in the Dry Fork area southwest of the Spring.

GEOLOGY OF THE MARAMEC SPRING AREA

Stratigraphy

The origin of Maramec Spring was a product of geology and weathering. The area is underlain mostly by Lower Ordovician (Canadian)-age and older sedimentary rock units, principally dolomites with lesser amounts of sandstone and finer clastics. There are some minor outliers of undifferentiated Pennsylvanian and Mississippian-age strata in the extreme northern and northwestern part of Dry Fork basin, but since these units have no bearing on Maramec Spring they will not be discussed in further detail. Figure 4 is a stratigraphic column of the central Ozark area showing the formations, their lithologies, and their hydrogeologic significance.

Precambrian-age igneous and metamorphic basement rocks underlie the area at a depth typically more than 1,000 ft. The Precambrian rock is overlain by several hundred feet of sandstone, dolomite, siltstone and shale units of Cambrian age consisting, in ascending order, of the Lamotte Formation, the Bonneterre Formation, and the Davis Formation. The lower two of these comprise the St. Francis aquifer, but it is hydrologically separated from the shallower aquifers by shales and siltstones in the Davis Formation, and does not appreciably influence shallower aquifers in the Maramec Spring area.

Three other Cambrian-age formations are present in the area and overlie the Davis Formation. In ascending order, these are the Derby-Doerun Dolomite, the Potosi Dolomite, and the Eminence Dolomite. The Derby-Doerun is a relatively low-permeability formation that is about 150 ft thick in the area. The Potosi Dolomite is much thicker and more permeable than the Derby-Doerun. In the Maramec Spring area it is about 250 ft thick, and is widely used as a target zone for municipal water supply wells in the region. It consists of coarsely crystalline, gray to brown dolomite. The unit normally contains little chert, but does contain quartz druse. The Potosi is not exposed at Maramec Spring or in its recharge area, but is exposed in the Crooked Creek structure east of the Meramec River near Cherryville.

The Eminence Dolomite overlies the Potosi, and is exposed in the area in the Crooked Creek structure. It also crops out along the Meramec River upstream from Maramec Spring in the Cook Station area. The Eminence is a gray, medium- to coarsely-crystalline gray dolomite and contains very little chert. The unit hosts most of the 10 largest springs in the Ozark region. Although Maramec Spring discharges from the formation above the Eminence, the deeper parts of the conduit system feeding the spring are developed in the upper 100 ft of the Eminence Dolomite.

Three Ordovician-age bedrock formations are exposed in the Maramec Spring area. The Gasconade Dolomite, from which the spring discharges, is about 350 ft thick, and is the basal Ordovician bedrock unit. It overlies the Eminence Dolomite and is exposed at Maramec Spring as well as along the parts of the valleys of Dry Fork , Norman Creek, and the Meramec River. Because of the dip or tilt of the strata, the

Gasconade is more widely exposed in the upper watershed of Dry Fork and Norman Creek than in the Maramec Spring area. Figure 5 is a generalized geologic and structure contour map of the study area (Anderson, 1979) showing the areal extent of formations cropping out in the area.

The Gasconade consists of three units- Upper Gasconade Dolomite, the Lower Gasconade Dolomite, and the Gunter Sandstone member. The Upper Gasconade is about 50 to 60 ft thick and consists of relatively chert-free, gray, medium-crystalline dolomite. The Lower Gasconade is also a dolomite, but has a much higher chert content. This part of the formation is also gray and is a medium- to coarsely-crystalline dolomite. Chert content in the

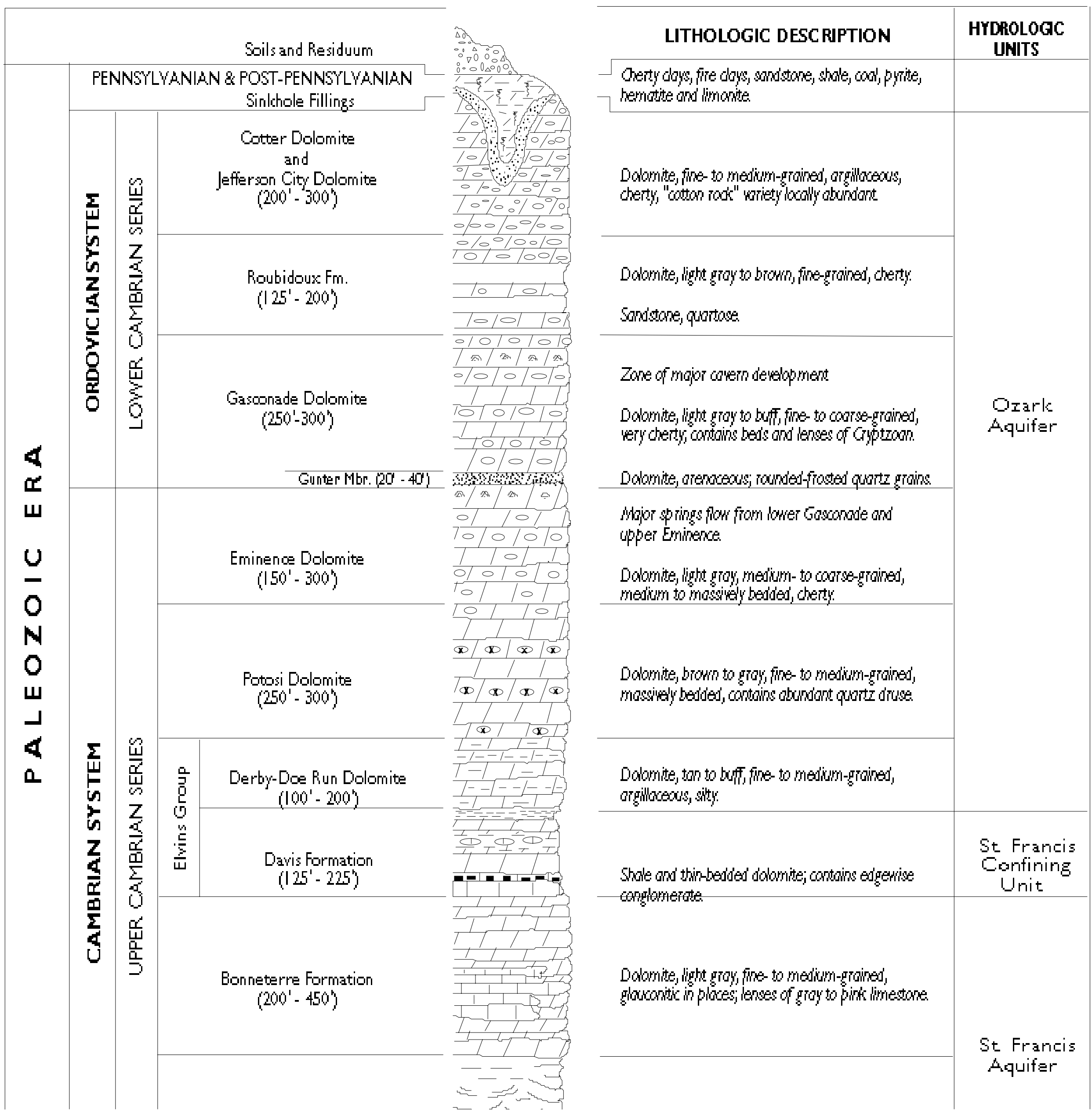
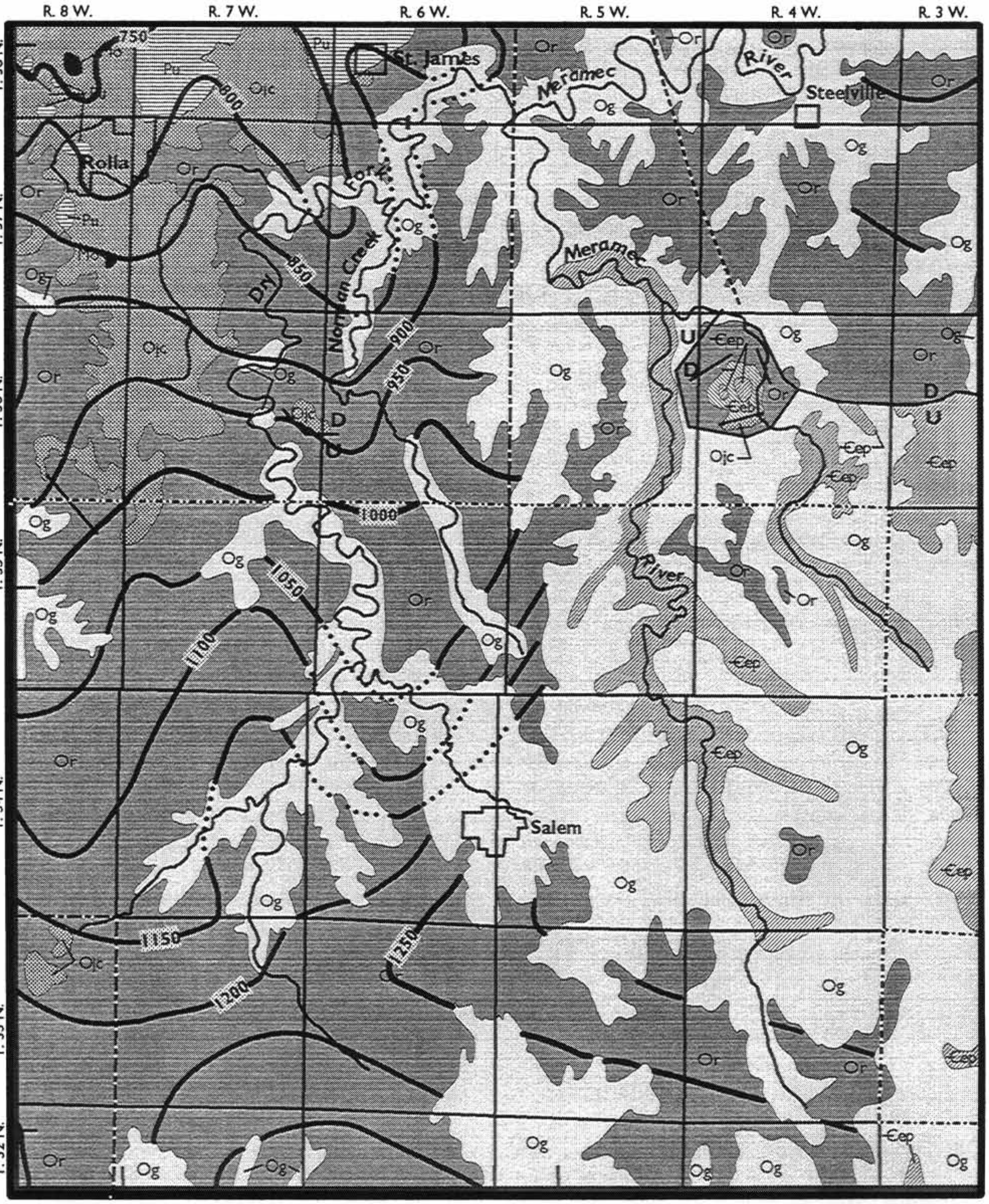


Figure 4. Generalized stratigraphic section showing the ages, names, lithologies, and hydrologic significance of geologic units in the central Ozarks.



LEGEND

Pu = Undifferenciated Pennsylvanian
Mo = Undifferenciated Mississippian
Ojc = Ordovician Jefferson City and Cotter Dolomites
Or = Ordovician Roubidoux Formation
Og = Ordovician Gasconade Dolomite
Єep = Cambrian Eminence and Potosi Dolomite
Єeb = Cambrian Elvins Group and Bonneterre Formation

Structure contours are feet above mean sea level, drawn on the base of the Roubidoux Formation

Faults: **U** = upthrown side; **D** = downthrown side

0 6
Scale in Miles

Figure 5. Geologic and structure contour map of the upper Meramec River basin area. Geologic information from Anderson and others, 1979. Structure contours from McCracken and McCracken, 1965.

Lower Gasconade can locally exceed 40 percent, and the thickness of this unit is about 225 ft. The Lower Gasconade commonly hosts large springs and caves in the Ozark region. The Gunter Sandstone member underlies the Lower Gasconade. In places in Missouri, the unit is predominately a sandstone; however, in the Maramec Spring area it is mostly a sandy, cherty dolomite that is about 25 ft thick. It is a very permeable zone and is wildly used as a target zone for high-yield water wells. It does not crop out at Maramec Spring or in Dry Fork basin, but is exposed along the Meramec River in the area near Cook Station in southwestern Crawford County. Total thickness of the Gasconade ranges from about 350 ft in the southwestern part of Dry Fork basin to about 280 ft in its northern end.

The Roubidoux Formation, a 125 to 150-ft thick unit of dolomite and sandstone, overlies the Gasconade and forms the bedrock surface throughout much of the Dry Fork basin. In this area, the lower 40 to 60 ft of the Roubidoux is mostly interbedded sandstone and cherty dolomite. On weathered surfaces, the sandstone can range in color from brown to red or gray. The dolomitic part of the formation is commonly gray to brown. Algal chert reefs are common in the dolomite units. The middle part of the formation is mostly massive sandstone that commonly exhibits cross-bedding, desiccation cracks, and current ripple marks, all indicative of deposition in a shallow, high-energy environment. The upper 30 ft of the Roubidoux is typically interbedded sandstone and dolomite.

In much of the Maramec Spring area, particularly the middle and upper sections of Dry Fork and Norman Creek in extreme southern Phelps County and adjacent parts of Texas and Dent counties, the Roubidoux has been very deeply weathered. Much of the carbonate rock in the unit has been dissolved away. The subsequent collapse of the sandstone beds has caused the remaining rock to be highly fractured as well as deeply weathered. The unit also thins in many places because of the lost carbonate rock. The net result of this weathering is deep residual soils in much of the area, and where the Roubidoux is intact, a very permeable bedrock unit.

The Jefferson City and Cotter dolomites cap the Roubidoux at higher elevations along the watershed divides in the northwestern part of the study area. The Jefferson City, oldest of the two units, has a maximum thickness of about 175 ft, and is thickest in the northwestern part of Dry Fork basin. The Cotter Dolomite overlies the Jefferson City and only occurs in the higher elevations in the northern part of Dry Fork basin where it has a maximum thickness of about 50 ft. Although these are considered separate stratigraphic units, their lithologic and visual characteristics are so similar that the units are considered a single unit for purposes of discussion. Both of these units are dolomites with minor chert, sandstone, and a few very thin shale zones. They are much less permeable than the Roubidoux, and have not been as deeply weathered.

Structural Geology

There are no mapped structural features within the Maramec Spring area that are known to influence its hydrology. Commonly, faults and other structural features have pronounced effects of groundwater movement. Certain faults act as barriers to groundwater movement. Others have provided an avenue for weathering, and the secondary permeability developed along them provides for increased groundwater movement. The few mapped faults in the Maramec Spring area are apparently of small displacement, and are mostly masked by the deep residual soils. The bedrock is heavily jointed, a likely result of periods of broad, gentle upwarping that have occurred in the area several times throughout the geologic past. Work by Williams and Martin (1963) show major joint sets to be roughly north-south and east-west. Joint-

ing has played a major role in development of surface valleys, as evidenced by the numerous straight stream and valley segments that parallel the major joint orientations.

The bedrock in the area generally dips to the north-northwest at about 16 to 20 ft per mile. Structural contours from McCracken and McCracken (1965), which are drawn on the base of the Roubidoux Formation, are shown on the geologic map. Like a topographic map shows the shape of the land surface, a structural contour map shows the shape of the boundary between two units. The area of the geologic map which contains no contour lines is where the Roubidoux Formation has been completely removed by erosion.

The geologic map shows the presence of a circular geologic structure east of the Meramec River about 10 miles southeast of Maramec Spring. This structure, generally referred to as the Crooked Creek structure, is one of several structural features occurring along the 38th parallel from eastern Kentucky, through Missouri, and into Kansas. They have been interpreted several ways by past workers, but current thinking considers them to be due to low-angle meteorite impacts (Hendriks, 1954).

KARST DEVELOPMENT

All of the bedrock units in the Maramec Spring area are predominantly dolomite, and the dissolving of them has created numerous caves, sinkholes, springs, losing streams, and other karst features that are so common in the Ozarks. Karst is a term used to describe areas where solution activity has played a major role in development of surface as well as subsurface drainage features. The Ozarks is known world-wide for its karst features. Although Missouri does not have the honor of having the longest, deepest, or largest cave, it nonetheless has an impressive number of caves. More than 5,500 caves are recorded.

Nine of Missouri's springs are classified as first magnitude, having discharges which average more than 100 cubic feet of water per second (ft^3/sec). There are many more second magnitude springs which have average discharges between 10 ft^3/sec and 100 ft^3/sec, and many smaller springs. A spring database maintained by the Division of Geology and Land Survey currently contains locations for about 2,900 springs.

Two other karst features, which may at first glance seem insignificant when compared to caves and springs, are present in great numbers and are responsible for much of the character of the Ozarks. Sinkholes and losing streams, like caves and springs, are karst features that have a very important function-they provide much of the surface drainage and, subsequently, much of the groundwater recharge that feeds the springs in the Ozarks.

Too commonly, karst features are viewed as separate entities rather than parts of a more complex system. A practical way of viewing karst features is by considering their function, not their form. The karst features discussed here can be divided into three categories-recharge features, transport features, and discharge features. Sinkholes and losing streams are groundwater recharge features. Runoff from precipitation is funneled directly into the subsurface by sinkholes and losing streams. Caves and other bedrock conduits are the avenues of movement for karst groundwater recharge, and springs are the outflow points. It must be remembered that without sinkholes and losing streams, as well as the subsurface openings that connect them with their outlets, springs like Maramec would not receive the volume of recharge they do. In much of the Salem Plateau, mostly air-filled caves that are enterable today are no longer functioning parts of a karst drainage system. Their functioning counterparts are still mostly below the water table, and will not be entered, except perhaps by divers, for many centuries to come.

The dimensions of most of the water-filled caves or conduits that transport water to springs are not known except perhaps for their last few hundred or few thousand feet where they are accessible to divers entering from spring outlets. Few major spring systems can be entered by man from locations other than the outlet. Water well drillers commonly report intersecting cave-like openings at various depths while drilling wells. Some of the openings are described as being only inches across, while others may allow the drill bit to drop several feet. These inaccessible, mostly water-filled cave open-

ings are often referred to as conduits, mostly to avoid confusing them with the mostly air-filled cave passages that can be entered by people.

The water-filled cave passage or conduit that channels the water from the mouth of Maramec Spring has been explored to a depth of about 190 ft and a distance of about 1,700 ft by SCUBA divers. Figure 6 is an underwater map of Maramec Spring that was produced by divers Roger Miller and Frank Fogerty (1978). By pre-staging tanks through the spring conduit and using a low-oxygen content air mixture, they were able to extend their time underwater to allow for the extensive exploration they made.

The spring outlet of Maramec Spring is about 4 ft high and 10 ft wide, and is beneath about 17 ft of water in the rise basin (Vineyard and Feder, 1982). During low-flow conditions when the water is calm and clear, the shadowy opening can be seen from the trail around the rise pool. Divers generally restrict their exploration to periods of low flow when the velocity of the water discharging from the mouth of the spring is low enough to navigate. Still, divers have to pull themselves through the constricted entrance. Just inside of the entrance the cave dimensions increase substantially as a water-filled chamber about 80 ft in diameter is entered. The cave continues downward from the back of this room. When divers had to turn back at the end of their exploration it was not because of the size of the water-filled cave. It was still 10 to 15 ft in diameter. They simply had reached the limit of their available diving technology. As equipment and techniques improve, the explored parts of the spring system will likely increase. Based on their map, at the point of farthest exploration Fogerty and Miller stopped about 1,350 ft almost due south of the spring outlet, about 200 ft below the bottom of Brown Hollow.

An interesting point to remember is that springs like Maramec are dynamic and still growing. The best evidence of this is found in the chemistry of the spring water. The water discharging from Maramec Spring, like most of the springs in the Salem Plateau, is a calcium-magnesium-bicarbonate type. The major cations (positively charged ions) that are dissolved in the water are calcium and magnesium, the main components of the dolomitic bedrock. The major anion (negatively charged ion), bicarbonate, also is derived from dolomite. The amount of dissolved calcium and magnesium contained in water discharging from Maramec Spring averages less than 50 mg/L, but represents about 50 tons of dissolved dolomite each day. This volume of rock, of course, comes from all of the recharge area, but it demonstrates that each day, the size of the openings within the spring system are slowly increasing.

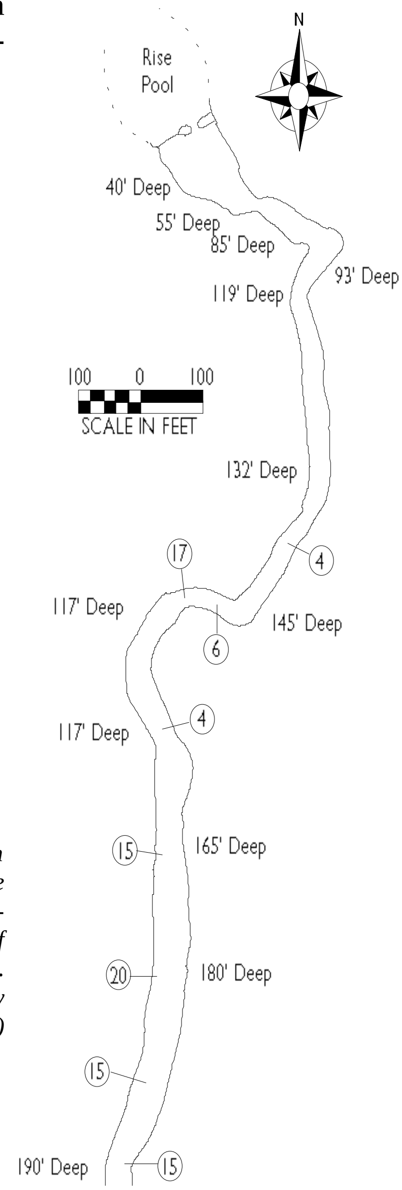


Figure 6. Plan map of the explored underwater extent of Maramec Spring. (Map by Fogerty and Miller, 1978.)

HYDROGEOLOGY

Maramec Spring is Missouri's fifth largest spring. It is one of only nine springs in Missouri with an average discharge greater than 100 ft^3/sec. Discharge data was collected by the U.S.G.S. at Maramec Spring for a 29 year period from 1903 to 1905, 1922 to 1929, and 1965 to 1985. During average flow conditions, Maramec Spring discharges about 155 ft^3/sec, or nearly 100 million gallons per day, into the nearby Meramec River, more than doubling the flow of the river most of the time. In comparison, it would take 69 water wells, each producing 1000 gallons of water per minute, to equal the average flow of Maramec Spring.

During the 29 year period of record, minimum and maximum discharges were 56 ft^3/sec which occurred August 1, 1934, and 770 ft^3/sec which was measured December 6, 1982. Discharges higher than this are known to occur, but are difficult to measure because backwater flooding from the Meramec River typically coincides with periods of very high flow at Maramec Spring. The highest discharge ever directly measured at Maramec Spring was done by the U.S.G.S. on November 17, 1993, when a discharge of 1,100 ft^3/sec was measured.

The Hydrologic Cycle

Water on Earth is a finite resource; there is essentially the same volume of water present today that there was in the distant past. The water in Missouri's streams, the water contained in its aquifers, and the water discharging from its springs all shares a common origin. It originates as precipitation falling upon the Earth's surface. Once precipitation strikes the Earth, physical and biological factors begin to change the distribution of the water. Part of the precipitation is evaporated back into the atmosphere before it can become either surface flow or groundwater recharge. Plants also transpire a tremendous volume of water. Both of these losses are highly dependent on season and temperature. The losses are, of course, much greater in hot weather during the growing season than during the late fall, winter, and early spring when vegetation is dormant. Normally, between 2/3 and 3/4 of the yearly precipitation is lost back to the atmosphere by evaporation and transpiration losses. The remaining water is considered yield, and is water that is available to become either surface-water runoff or groundwater recharge. Figure 7 graphically depicts the hydrologic cycle in a karst area such as the Ozarks.

Long-term temperature and precipitation data are available from two National Weather Service stations within the area. There are 112 years of precipitation data and 96 years of temperature data available from Rolla-UMR, which is on the University of Missouri-Rolla campus and operated by the Geology and Geophysics Department. The Salem station, operated by the National Forest Service, Mark Twain National Forest, is about 1/4 mile south of the Missouri Highway 72-19 junction on the south edge of Salem. Precipitation data has been collected here for 98 years, and temperature data for 92 years. Long-term

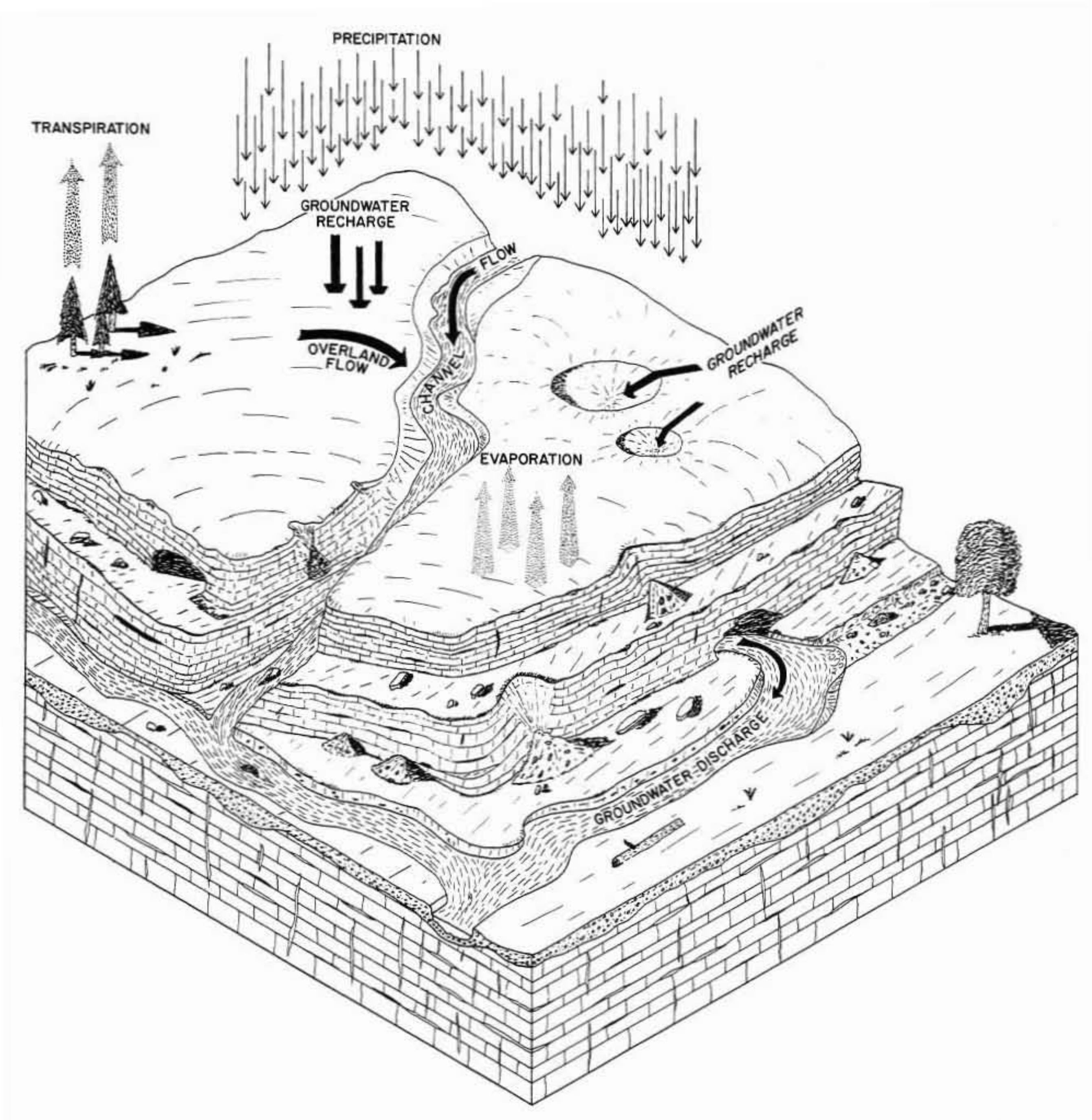


Figure 7. The hydrologic cycle components in a karst area.

average monthly and yearly temperatures and rainfall are shown in table 1.

January, with an average temperature of 28.7°F, and July, with an average temperature of 78.3°F, are the coldest and warmest months at Rolla. The same holds true at Salem where January temperature averages 31.7°F, while that for July is 77.8°F. Average yearly temperature at Rolla-UMR is 54.9°F, and at Salem it is about 1.3°F warmer, 56.2°F (Nat. Climatic Data Center, 1995).

Average annual precipitation at Rolla-UMR averages 41.09 inches. January is the driest month with an average precipitation of 1.70 inches, while May is the wettest with an average precipitation of 4.78 inches. Average rainfall in every month except January and February averages more than 3 inches at Rolla-UMR. These values are based on data collected through 1995.

Although long-term precipitation data has been collected at Salem, short periods of missing data in 1994 and 1995 preclude the National Weather Service from publishing a full suite of long-term average precipitation data that includes these years. Long term monthly and yearly values are available through 1993. Based on these, January is the driest month with an average precipitation of 2.00 inches while May, with 4.43 inches, is the wettest month. Average yearly precipitation is 42.1 inches.

There was above normal rainfall for the years 1993, 1994, and 1995 in the Maramec Spring area. Rolla-UMR reported 64.77 inches in 1993, which is 23.68 inches above normal. Precipitation in 1994 at Rolla was 47.95 inches, 6.86 inches greater than normal, and it was 9.01 inches above normal in 1995 with the yearly total being 50.01 inches. Total precipitation in Salem in 1993 was 57.85 inches, 15.76 inches above normal. Yearly values are not available for 1994 and 1995 due to missing data.

Month	Rolla Temp. (°F)	Rolla Precip. (in.)	Salem Temp. (°F)	Salem Precip. (in.)
January	28.7	1.70	31.7	2.00
February	33.2	2.22	36.2	2.34
March	44.0	3.49	46.5	4.08
April	56.0	3.58	57.4	4.04
May	65.0	4.78	65.2	4.43
June	73.2	4.11	72.9	3.30
July	78.3	3.81	77.8	3.37
August	76.5	3.60	75.9	4.26
September	68.5	3.55	68.9	3.90
October	57.1	3.60	58.5	3.19
November	45.2	3.58	47.3	3.82
December	33.1	3.07	35.8	3.37
Total precip.-Avg. temp.	54.9	41.09	56.2	42.10

Table 1. Long-term temperature and precipitation data, Rolla-UMR and Salem. (Data source: Nat. Climatic Data Center, 1993, 1995)

The losses of water to evaporation and transpiration, together referred to as evapotranspiration, are not routinely determined. Both are very difficult to measure, and normally are estimated or calculated using any of several techniques. The Thornthwaite method (Thornthwaite and Mather, 1955) uses temperature and precipitation data, adjusted for latitude, day length, and other factors, to estimate the potential evapotranspiration, which is the evapotranspiration that would take place if adequate soil moisture was available at all times. In reality, though, the actual evapotranspiration is considerably lower than the potential evapotranspiration. Potential evapotranspiration is highest during the hottest summer months, June, July, and August, and lowest when temperatures are cooler. Water yield, which is the water that is available for surface-water runoff and groundwater recharge, is essentially the volume of water from precipitation minus the losses to evapotranspiration, corrected for changes in soil moisture storage. Thus, the months of highest runoff and recharge normally are the wetter spring months when temperatures are still cool and evapotranspiration is relatively low. Except during very wet years, rainfall during the late summer (mid-July through September) is considerably less than the potential evapotranspiration, and there is normally little or no surface-water runoff or groundwater recharge during this period.

A hydrologic budget, which numerically describes precipitation, evapotranspiration, and yield, was not calculated for the Maramec Spring area. However, Vandike (1992) calculated a hydrologic budget for the Bennett Spring area about 60 miles west of the Maramec Spring area. Since both areas share a similar climate and latitude, the distribution of water should also be similar. The Bennett Spring hydrologic budget showed that of an average precipitation of about 41 inches, approximately 27 inches of moisture was lost to evapotranspiration, with the remaining 14 inches available for surface-water runoff and groundwater recharge.

The total volume of water available for surface-water runoff and groundwater recharge can be estimated by looking at flow hydrographs of major streams and rivers in the area of interest. Though a river's flow is generally considered surface water, it actually consists of a mixture of surface water and groundwater. Water entering a river following periods of heavy rainfall is mostly direct surface-water runoff, and is responsible for higher river stages. However, in the Ozarks most rivers have well-sustained, dry-weather base flows that are provided by springs and general groundwater inflow to the streams. Streams in other areas of Missouri do not all share this characteristic. Most of northern Missouri is underlain by glacial drift consisting of a mixture of clay, silt, sand, and gravel that was emplaced by glaciers during the Ice Age. The glacial drift typically has a low permeability, and though it stores appreciable volumes of groundwater, it takes it into and releases it from storage very slowly. Streams in northern Missouri, even those draining more than a thousand square miles, have very low dry-weather flows. Figure 8 helps illustrate this. It shows flow-duration curves for two rivers with very similar drainage areas and runoff rates, but very different hydrogeologic conditions. A flow-duration curve shows the percentage of time that a particular flow is equaled or exceeded. The North River near Palmyra drains an area of 373 mi^2. Its watershed is almost entirely underlain by low-permeability glacial drift. The Jacks Fork drains a similar size area, 398 mi^2, but is underlain by Ordovician and Cambrian age dolomites. There is considerable groundwater recharge in the upland areas of the Jacks Fork, and numerous springs, large and small, along its length. The largest of these is Alley Spring, which has an average discharge of about 125 ft^3/sec. The differences in the flow-duration curves of these

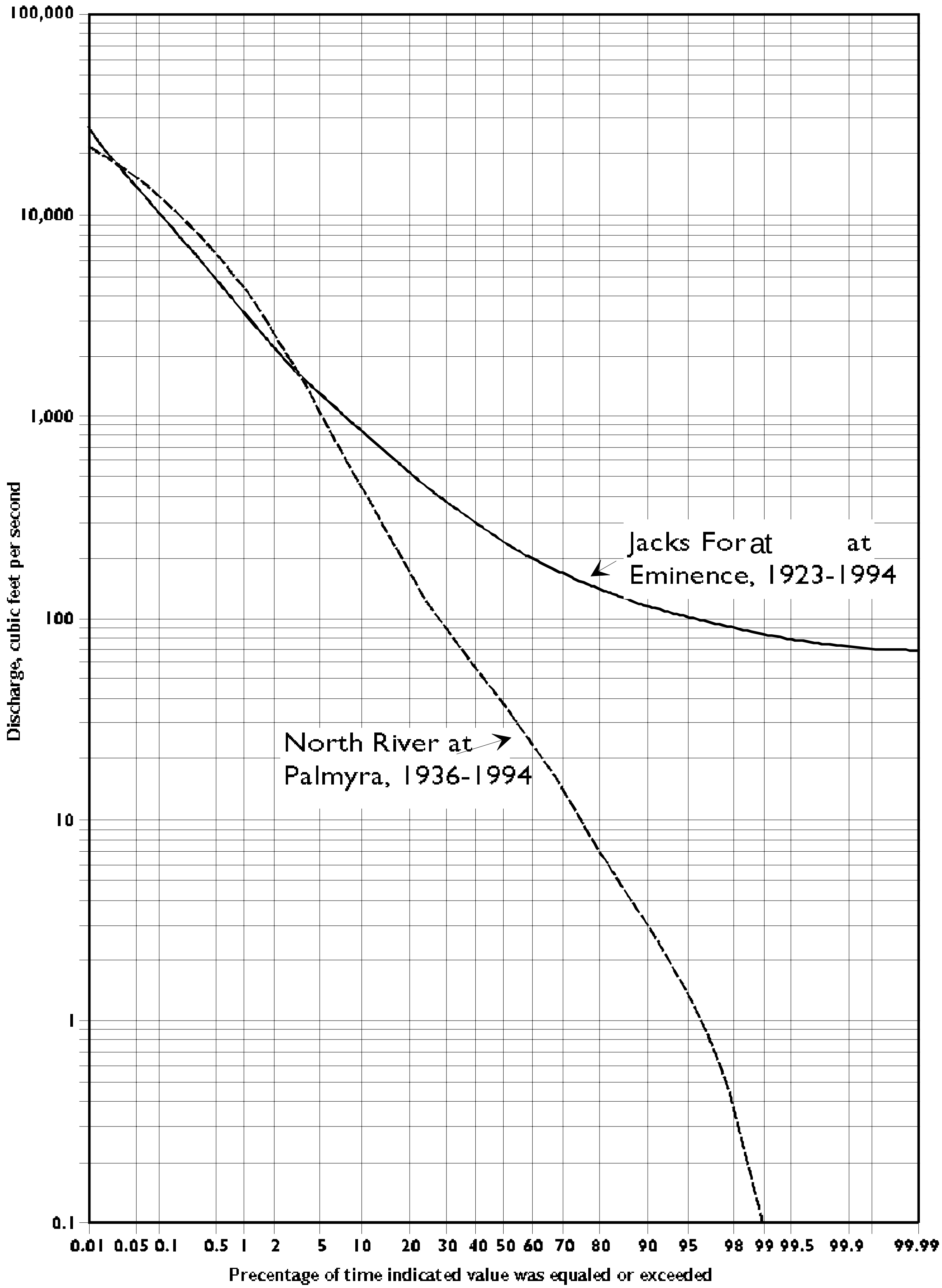


Figure 8. Flow-duration curves of the North River at Palmyra and the Jacks Fork near Eminence.

two streams can be attributed to their different hydrogeologic conditions. The North River receives very little groundwater inflow, and during dry weather its flow continuously decreases until, in extremely dry conditions, reaches zero and the river becomes a series of pools. The Jacks Fork receives a large volume of groundwater inflow, and even in during very dry conditions it continues to have a relatively large discharge. Most major Ozark rivers have flow characteristics that are similar to those of the Jacks Fork, with well-sustained base flows provided by groundwater (Vandike, 1995).

Groundwater Recharge

Groundwater recharge in the Ozarks can be categorized into two broad types: Diffuse recharge and discrete recharge. Diffuse recharge results from the slow downward percolation of water from precipitation through the soil materials, through smaller bedrock openings, until it reaches the water table. The water table is the two-dimensional surface which forms the boundary between mostly air-filled openings above it and water-filled openings below it. Diffuse recharge occurs nearly everywhere, with amounts greater where the surficial materials and underlying bedrock are most permeable, and least where they are not.

Discrete recharge occurs only where there are specific geologic features that allow large quantities of water to enter the subsurface with little resistance, predominately in sinkholes and losing streams. Sinkholes are bowl-shaped, topographic depressions in the Earth's surface that formed by the dissolving of bedrock and the subsurface removal of soil and rock (figure 9). Sinkholes act as natural funnels. Runoff from precipitation that enters them is channeled directly into the subsurface through relatively large openings.

Figure 9. Photograph of a large sinkhole in Dry Fork basin. Photo by Jim Vandike.

Gaining streams are those streams that maintain their flow or increase flow in the downstream direction. Losing streams, as the name implies, are those drainages that lose a major part of their runoff into the subsurface (figure 10). They function much like sinkholes in that there are relatively large bedrock openings that drain water from the losing streams and channel it to the receiving springs. Unlike sinkholes, water-loss zones along losing streams typically have no surface expression. The bedrock openings that so efficiently steal the flow are generally concealed beneath a veneer of coarse gravel and sand. Some losing streams lose flow only in specific places while others lose flow throughout long sections of their course. In most of the Ozarks, losing streams are responsible for most of the discrete groundwater recharge. Unlike sinkholes, most losing streams do not channel all of the runoff that enters them into the subsurface, especially during very wet weather. After heavy, prolonged precipitation there is generally so much runoff that only part of it is lost underground; the remainder leaves the basin by surface-water flow.

Losing streams, like other karst features, are the result of the dissolution of the carbonate bedrock. They are a result of the weathering, not the cause of it. Losing streams can be identified several ways such as by the loss of flow from the stream, by the characteristics of the alluvial materials in the streambed, by vegetation types, and other factors. Losing streams are subsurface drainage features. Water levels in the aquifer are generally lowest along losing stream reaches, and adjacent to the conduits that channel water from losing streams to springs. Thus, water in the aquifer moves toward the conduit, not away from it. Since the conduits serve as drains for the

Figure 10. Photograph of a losing reach of Dry Fork at Phelps County Road 4080 (formerly Spring Hill Road). Photo by Jim Vandike.

surrounding aquifer, water levels in the aquifer are typically well below stream-bed elevation along losing streams. Water levels in the aquifer near the conduits are also generally deeper than they are away from the conduits.

Vandike (1992) measured flow losses from several losing streams in the Bennett Spring area, and found that average annual runoff rates of the losing streams were quite low, as little as 10 percent of the flows that would be expected from gaining streams draining similar size watersheds.

Sinkholes, which can be identified from topographic maps, are most common at the southern end of the upper Meramec River basin, particularly in the surface-water drainage divide area between Dry Fork and the Current River basin. Although there are likely several hundred sinkholes in the area, they drain a relatively small area when compared to the part drained by losing streams.

The effects of discrete recharge can easily be seen by visiting Maramec Spring during dry and wet weather. The photo-

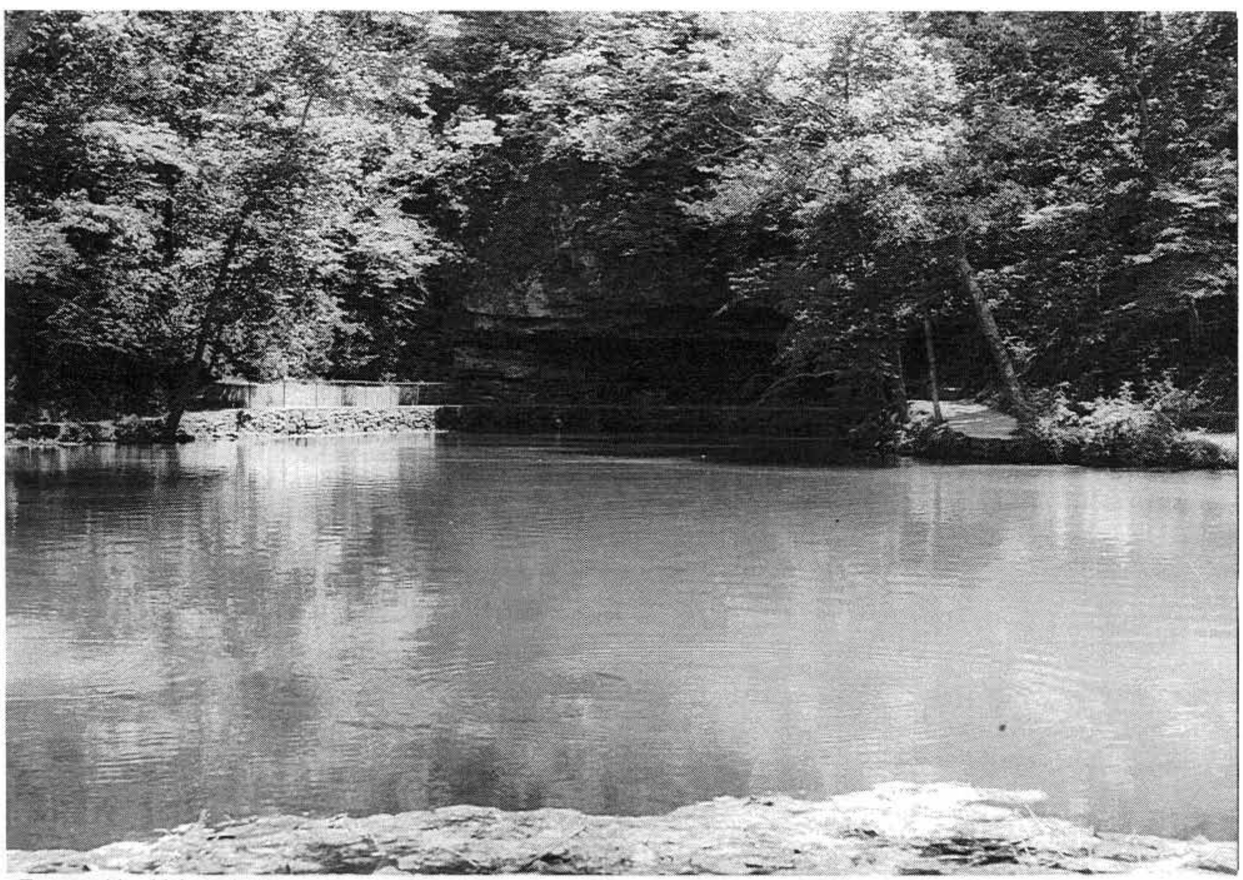


Figure 11a-11d. Photographs showing Maramec Spring rise pool and dam during low flow and high flow conditions. Photos by Jim Vandike.

graphs in figure 11 illustrate the differences between the spring during relatively low and very high flow conditions. During low-flow periods, the water surface in the rise pool above the spring outlet is calm, and boulders in the rock dams are exposed (figures 11a and 11b). The photographs shown in Figure 11c and 11d were taken December 4, 1982, after two days of very heavy rainfall. Rolla-UMR reported 6.54 inches of rain on December 3 and an additional 1.96 inches on December 4, a total of 8.50 inches during the two days. Salem reported 5.41 inches on December 3, and 1.06 inches on December 4, a total of 6.47 inches. The peak discharge measured by the U.S.G.S. at Maramec Spring in conjunction with this storm was 770 ft^3/sec on December 6.

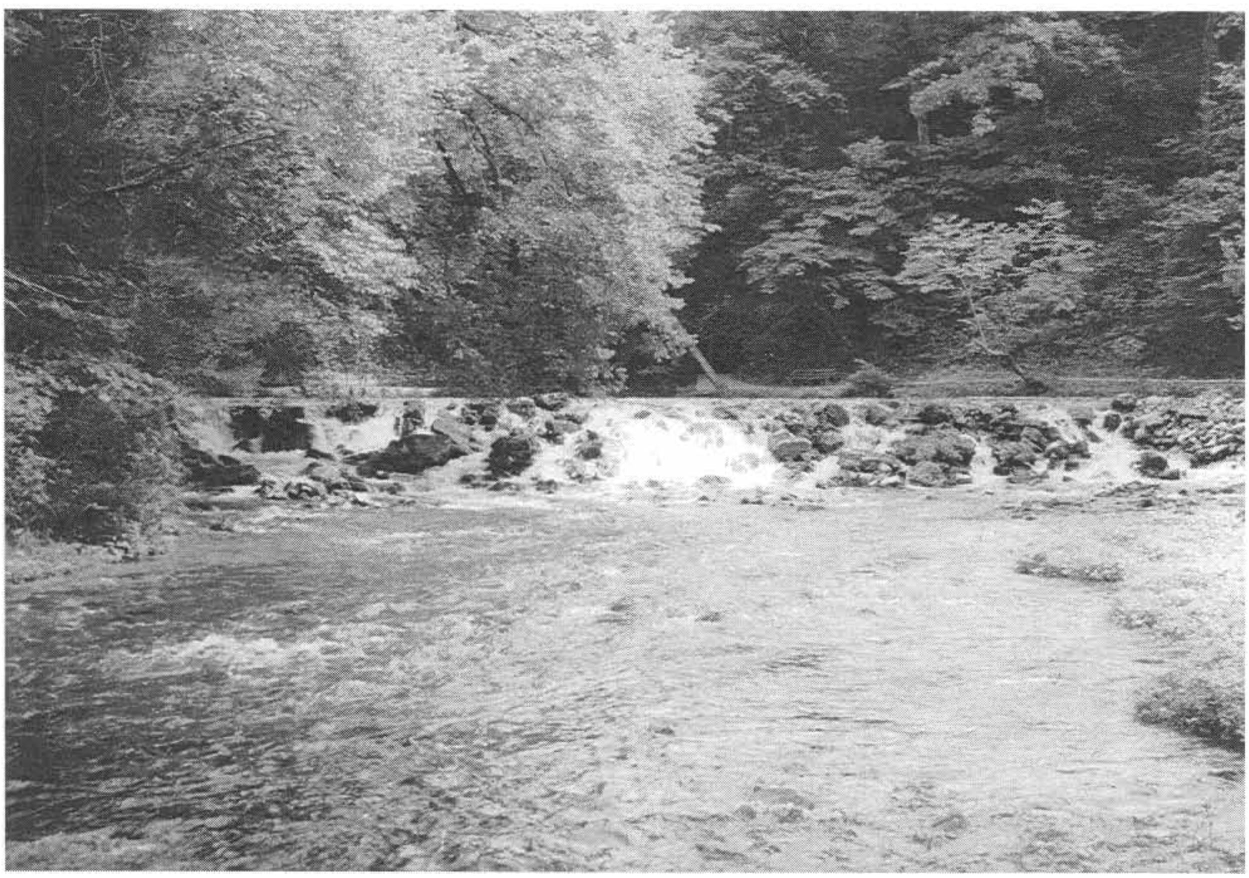


Figure 11b.

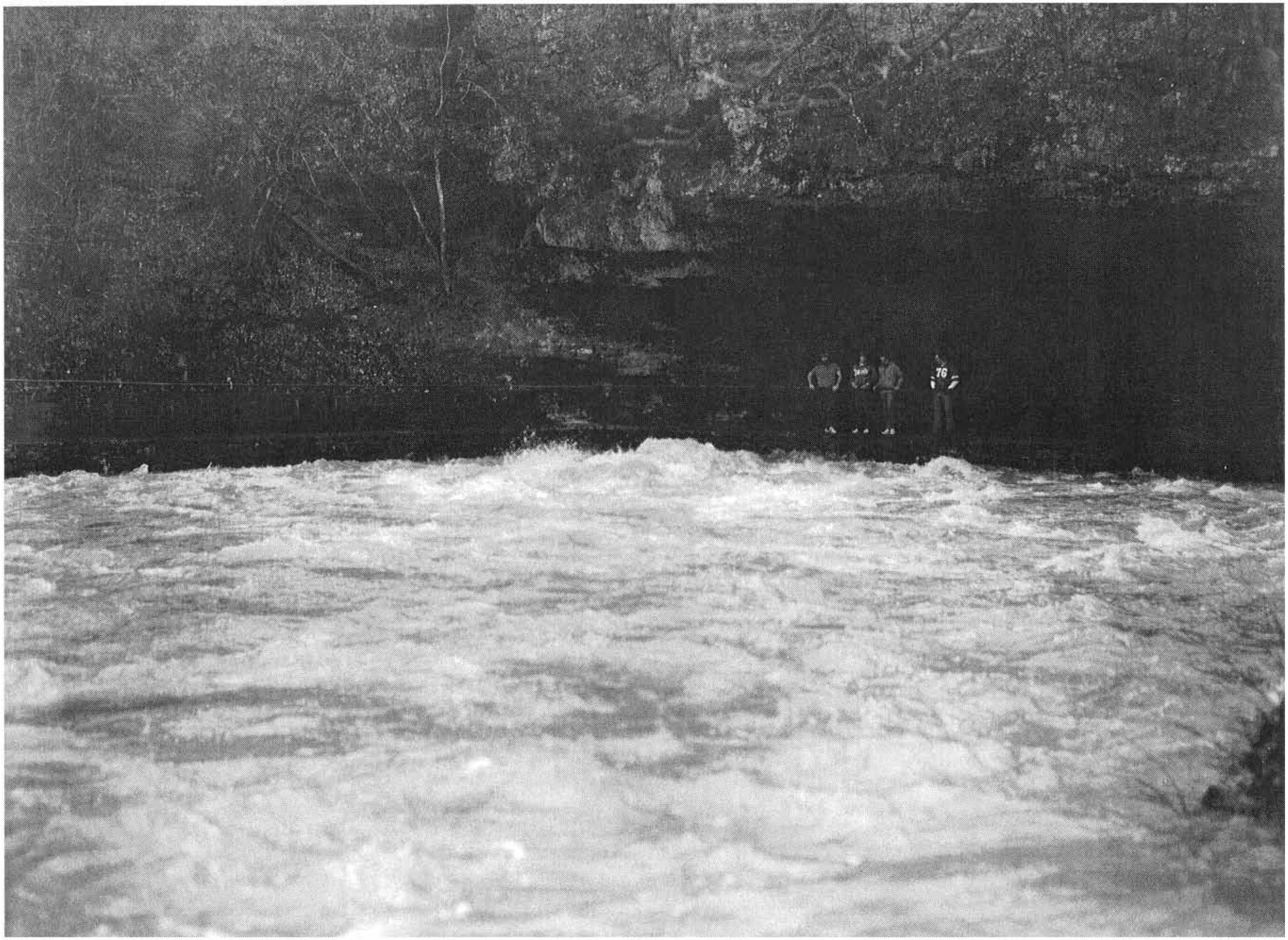


Figure 11c.

Figure 11d.

Flow Characteristics of Streams in the Study Area

The fact that some streams in the upper Meramec River basin carry little or no flow during dry weather is not a recent discovery. Nathanial Cook's plat map of the Maramec Spring area shows only two named streams: the Merrimac River, and the Dry Fork of the Merrimac River. The formal names of losing streams in the Ozarks commonly reflect their flow characteristics. Dry Creek, Dry Fork, Lost Creek, Sinking Creek, and others with similar names generally prove to be losing streams. Dry Fork, as it is known today, is the largest upper Meramec River tributary, and one of the more notable losing streams in south-central Missouri. Dry Fork drains an area of 383 square miles. The Meramec River upstream from Dry Fork drains only 343 square miles. But despite its larger drainage area, Dry Fork normally carries considerably less flow than the Meramec River. Downstream from Missouri Highway 32 east of Salem, the Meramec River has permanent flow and is considered to be a gaining stream. However, only in two sections is Dry Fork considered to be a gaining stream. It contains a gaining reach the southern part of the basin and another in the northern end. Losing reaches are found in the upper part of the watershed and, most notably, in the middle section roughly from Phelps County Route F to a few miles upstream of Missouri Highway 72. Barnitz Prong and Spring Creek, two upper Dry Fork tributaries, are gaining streams throughout most of their lengths, but their flows are normally lost into the subsurface farther downstream in losing-stream sections of Dry Fork.

Seepage runs are typically performed to delineate gaining and losing-stream sections of streams. A seepage run consists of a series of flow measures taken at numerous crossings of a stream in as short a time as possible. They are typically conducted in the late summer and early fall when conditions are dry and flows unlikely to change during the period when the measurements are taken. Decreases in flow in a downstream direction indicate losing-stream conditions, while no change or increases in flow indicate a gaining stream. Data from two seepage runs conducted in Dry Fork watershed are shown in figure 12. One run, conducted by the U.S. Geological Survey in November 1969, was made during very dry weather (Skelton, 1976). A second run, conducted by the Division of Geology and Land Survey in February 1982, was made during wetter conditions.

The 1969 seepage run showed that there was no flow in Dry Fork upstream from Phelps County Route F except for a short reach below the confluence of Spring Creek with Dry Fork. The measurements showed Little Dry Fork to steadily gain flow downstream from Rolla. Norman Creek at this time was essentially dry from headwaters to mouth. The 1982 seepage run showed a similar overall flow pattern, but because it was made during wetter conditions there was flow in several stream reaches that had been dry during the first run. The 1982 seepage run showed that Barnitz Prong provided perennial inflow into Dry Fork in the upper part of the watershed, and that although flow steadily decreased between the mouth of Barnitz Prong and Spring Creek, there was continuous flow in Dry Fork. Inflow from Spring Creek helped maintain flow in Dry Fork for the next several miles downstream, but by the first county road crossing north of the Phelps-Dent County line, Dry Fork had no flow and remained dry for the next several miles. Upper Norman Creek had flow at this time, but it disappeared underground a short distance north of the Phelps-Dent County line, and was mostly dry the remainder of its length.

A smaller but even more classic example of a losing stream is Norman Creek, Dry Forks largest tributary. Norman Creek drains an area of about 52 square miles. It is a losing stream throughout the lower watershed from a short distance down-

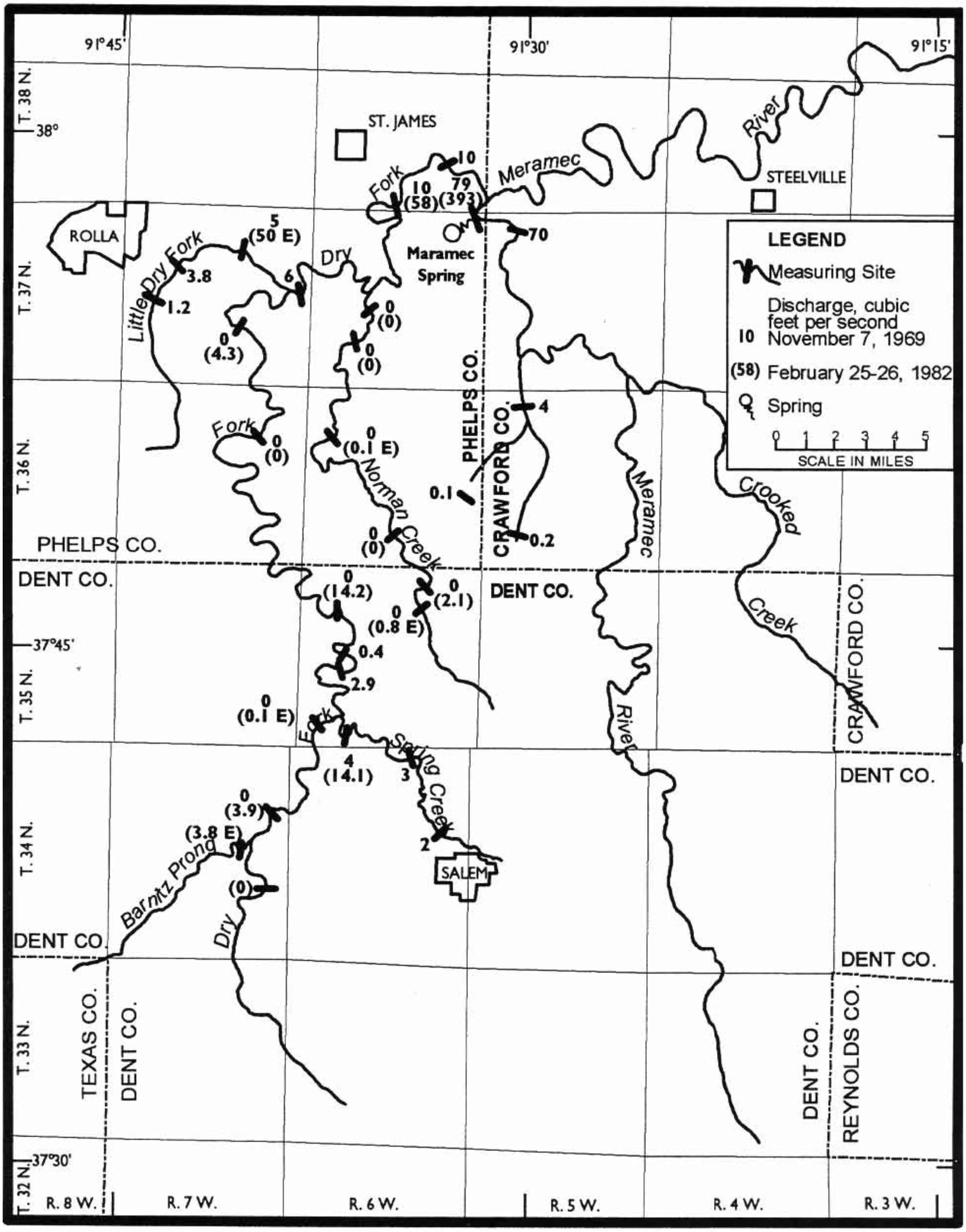


Figure 12. Seepage run data for the upper Meramec River basin including Dry Fork and Norman Creek.

stream of Phelps County Route JJ near Seaton to its confluence with Dry Fork about 4 miles west of Maramec Spring.

Watershed Reconnaissance

Dry Fork and Norman Creek are not the only losing streams in the upper Meramec River basin and in adjacent watersheds. A watershed reconnaissance was performed to help determine the locations of losing streams which provide groundwater recharge to Maramec and other springs, and also to delineate gaining streams that benefit from groundwater inflow. The reconnaissance included parts of the Meramec River, Current River, and Gasconade River basins. In the Meramec basin it included Dry Fork, Asher Hollow, and the Meramec River basin upstream from Missouri Highway 8. In the Current River basin it included Barren Fork, Sinkin Creek, Gladden Creek, Pigeon Creek, and other smaller watersheds draining the area north of the Current River. In the Gasconade River basin it included Piney Creek upstream from Lane Spring, and Spring Creek upstream from Relfe Spring.

Streams within this area were examined at public access points such as county road and state highway crossings. Selected streams requiring a more detailed examination were, where possible, examined on foot. This was normally done where searching for suitable dye injection sites. Figure 13 shows the locations of major gaining and losing streams delineated in this study. The losing streams identified here are based on a practical definition of the term losing stream, which it is any drainage that channels a significant part of its flow into the groundwater system. The legal definition, which is found in the Missouri Clean Water Commission Water Quality Standards (10 CSR 20-7.015) is somewhat different. It states, in part that:

A losing stream is a stream which distributes thirty percent (30%) or more of its flow through natural processes such as through permeable geologic materials into a bedrock aquifer within two (2) miles flow distance downstream of an existing or proposed discharge. Flow measurements to determine percentage of water loss must be corrected to approximate the seven (7)-day Q_{10} stream flow. Thus, not all of the losing streams shown in this report may be considered losing streams under strict interpretation of the law. Most, however, would be. Also, because of map scale, only major drainages are shown. Many smaller tributaries of the major drainages that are shown are also losing streams.

Hydrologic Instrumentation

A major goal of this study was to gain a better understanding of the physical hydrology of the Maramec Spring system. This was done by measuring discharge and water quality changes at Maramec Spring, and relating it to precipitation in the recharge area. Excellent long-term precipitation data are available from both Rolla and Salem. However, the 25 mile distance between these stations is mostly Dry Fork basin. It was felt that the distance between the two precipitation stations was too great to ensure accurate rainfall data within the main part of the recharge area. Three temporary precipitation stations were established in Dry Fork basin to help fill the gap between Rolla and Salem. Each station consisted of a tipping-bucket rain gage and a digital recorder (figure 14). Precipitation enters the rain gage through cylinder at the top, and is funneled through its base into one of two tipping buckets that are mounted on either side of a fulcrum. When the bucket fills, which occurs each 0.01 inch of rainfall, its weight causes it to tip and bring the second bucket into position below the funnel. The first bucket then automatically empties. Each time the buckets tip, a magnet passes a reed switch, causing it to momentarily close and complete an electrical circuit. Each time the switch closes, the recorder advances 0.01 units. The recorders were set to cycle each hour on the hour, recording the values on paper

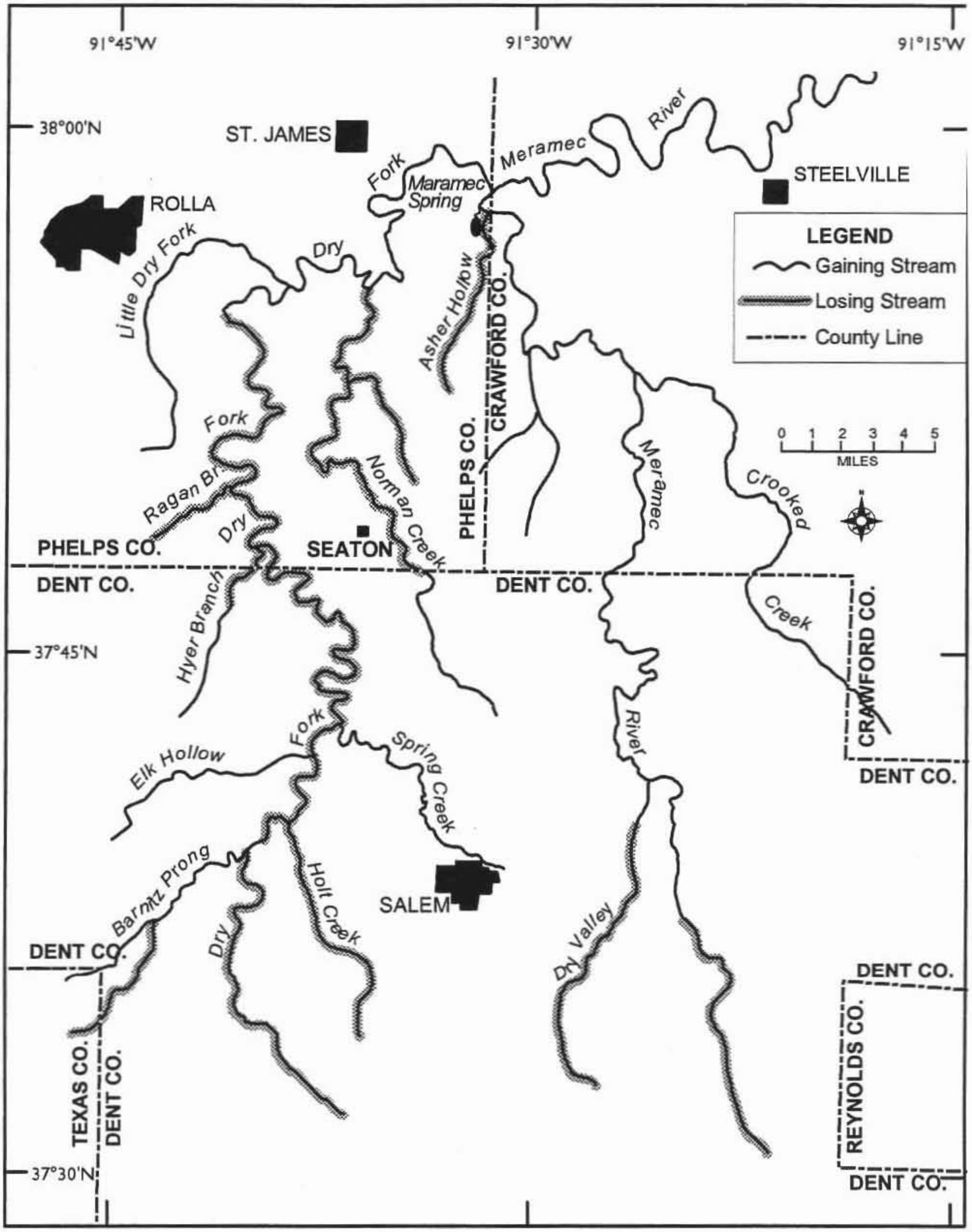


Figure 13. Losing streams in the Maramec Spring area.

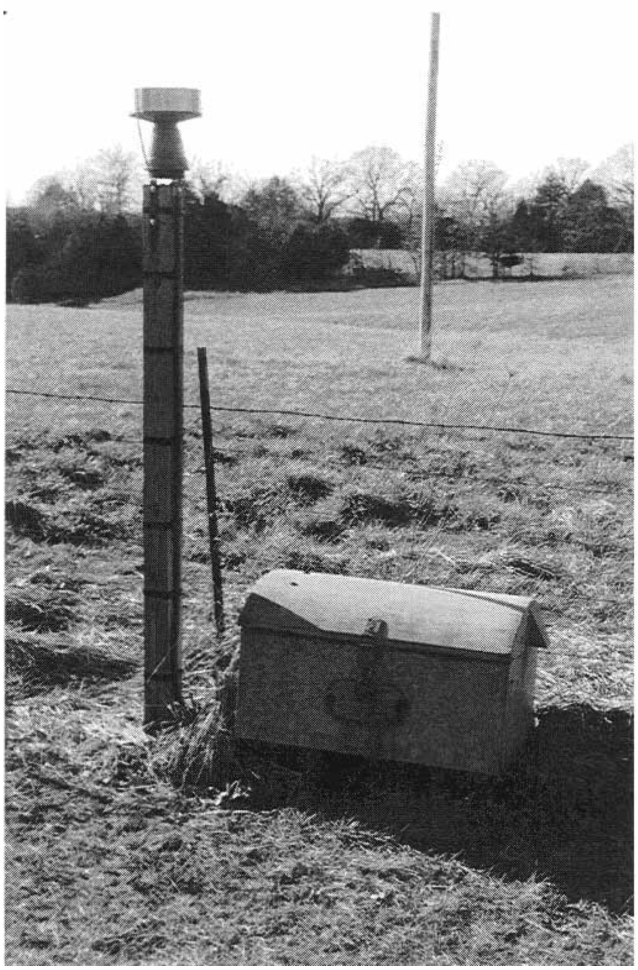


Figure 14. Automatic rainfall recording station in Dry Fork watershed (Dry Fork #1). Photo by Jim Vandike.

punch tape. The difference between successive values on the tape is the rainfall that occurred the preceding hour. Figure 15 shows the locations of the precipitation stations used during this study.

All three precipitation stations generally functioned well except during freezing weather when they would commonly malfunction. They were invaluable, though, in obtaining accurate information as to when rainfall began, and also hourly rainfall intensity. Daily precipitation values for all of the precipitation stations in the area are shown in appendix 1. Bar graphs depicting daily precipitation for the precipitation stations used in this study are shown in figure 16.

The discharge of Maramec Spring was recorded for many years by Department of Conservation personnel who made daily observations of the staff gage on the spring branch. The U.S.G.S. maintained the rating curve for the spring, and published discharge values for the spring through 1985 when funding constraints caused the station to be discontinued. In November 1985, at the beginning of a cooperative study with the University of California-Santa Cruz, the Division of Geology and Land Survey installed a digital water-level recorder next to the staff gage on the bridge over the spring branch. The instrument recorded hourly stage-height values that were converted to discharge values using the U.S.G.S. rating curve. The recorder was left in place to gather stage data after the one-year study ended in December 1986, but manual discharge measurements to keep the rating curve current were not made on a regular basis.

The rating curve was revised during the current study by making numerous discharge measurements at different stage heights. However, equipment was not available to make discharge measurements during high flows, so discharges above about 300 ft^3/sec are based on previous rating curves, and should be considered only estimates.

Hourly discharge data were collected at Maramec Spring during 1994 and 1995. Tables 2 and 3 show average daily discharge data for Maramec Spring for these years. The recorder operated continuously with no lost data except for two periods during floods when the installation was inundated by backwater from the Meramec River. After the second flood in 1994, the recorder box was moved from beneath the foot bridge to the top of the bridge rail, which greatly reduces the chances of future inundation.

A specific conductance probe and data logger was installed at the gaging station to

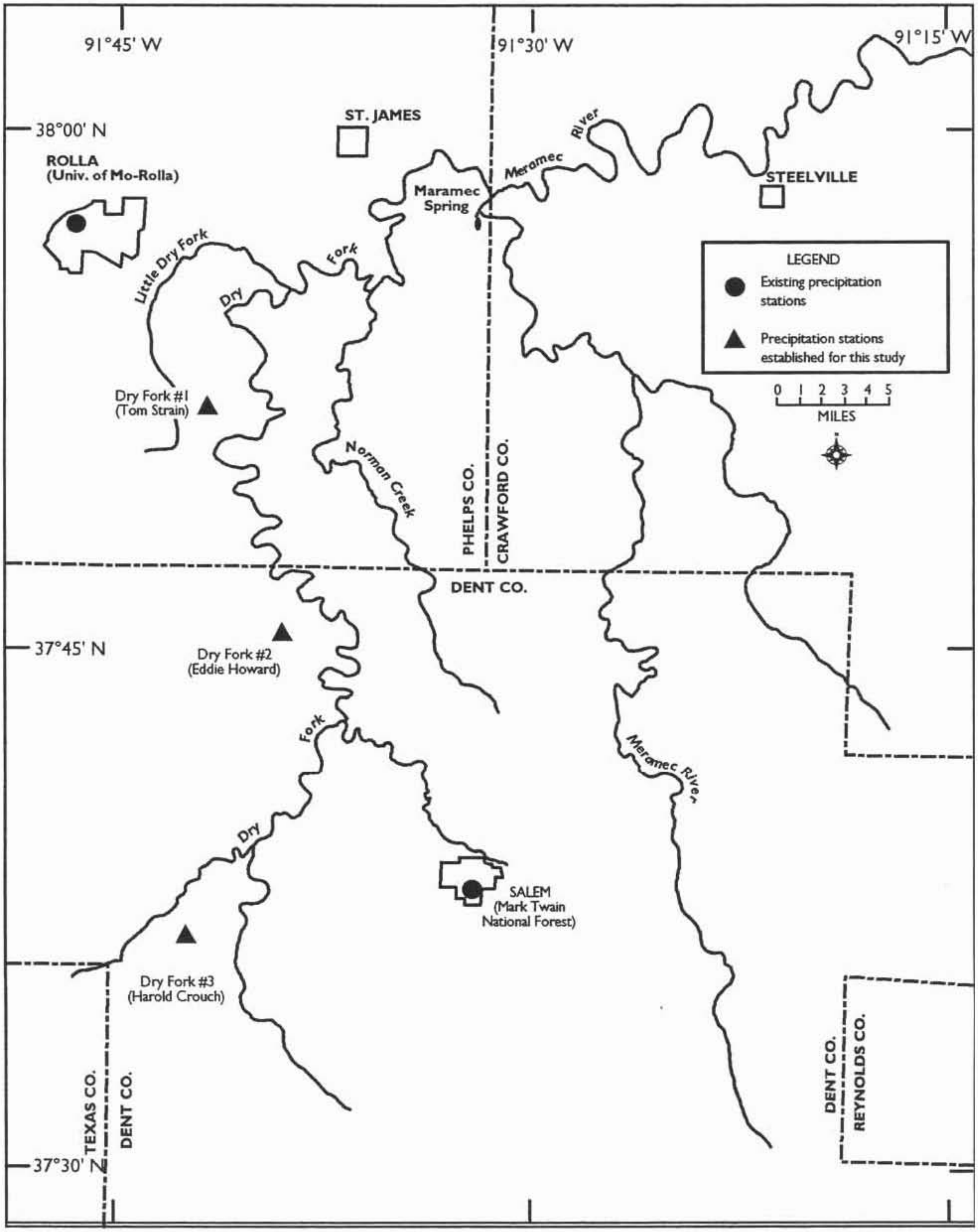
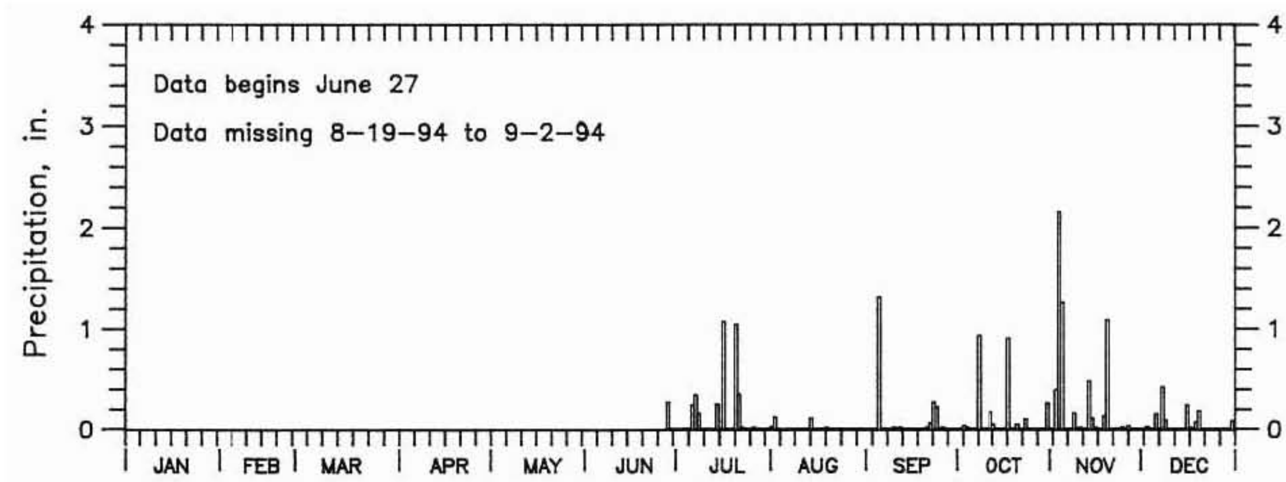
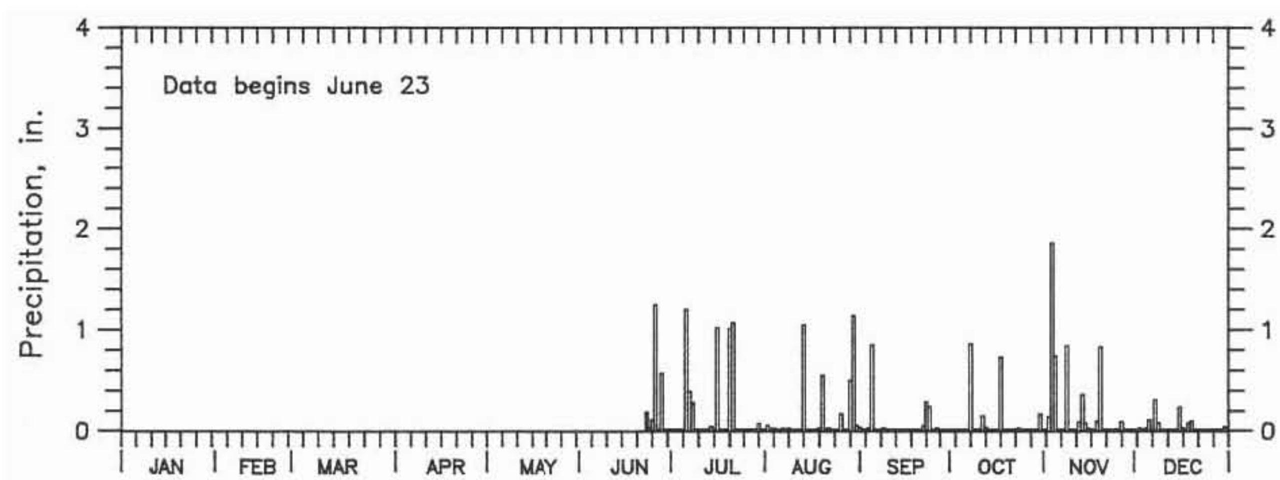


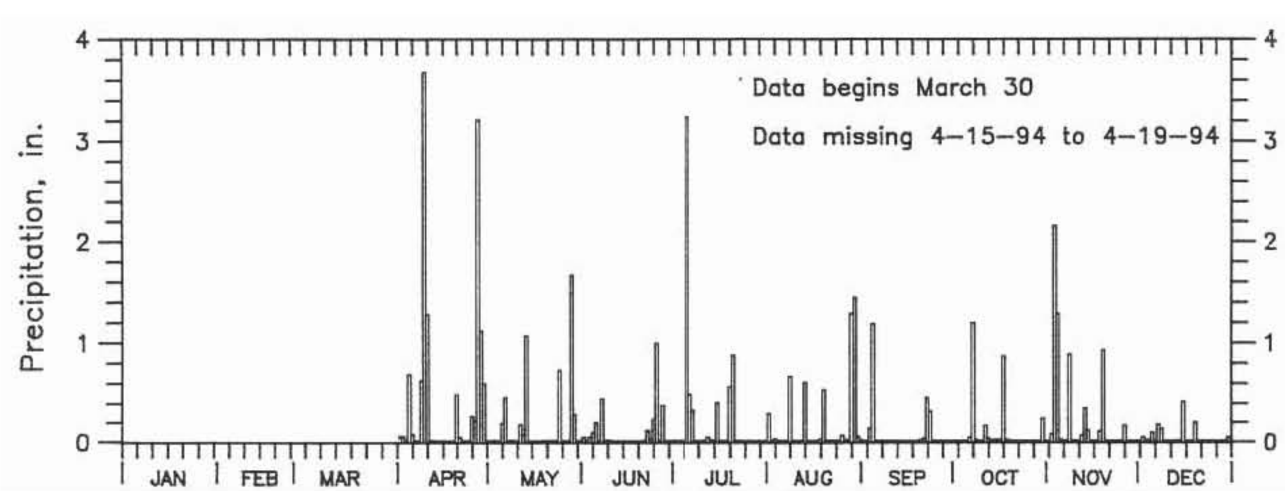
Figure 15. Locations of precipitation stations used in this study.



DRY FORK #3, 1994

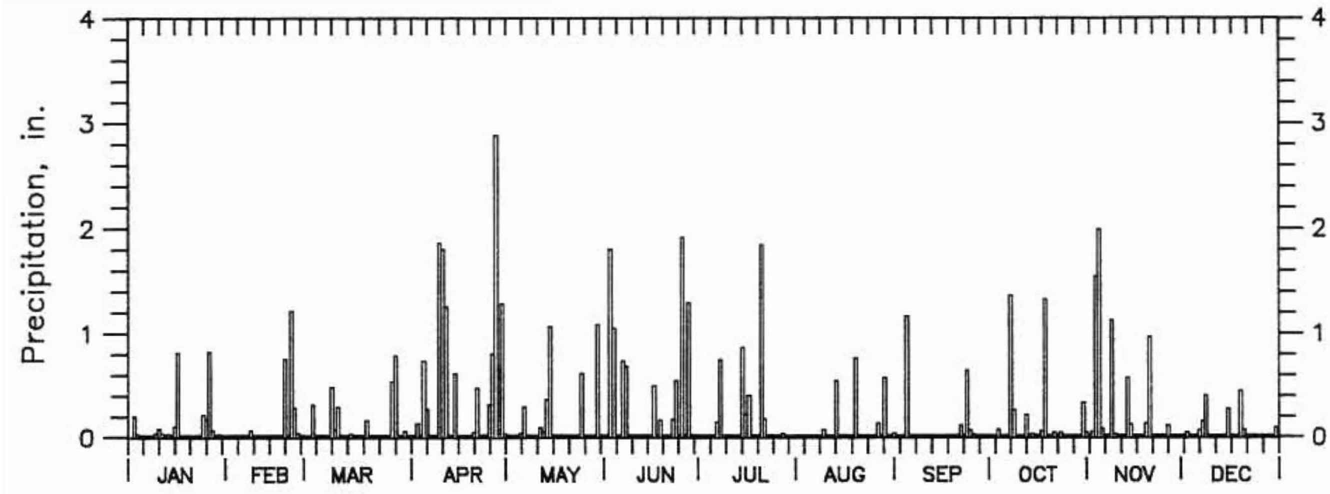


DRY FORK #2, 1994

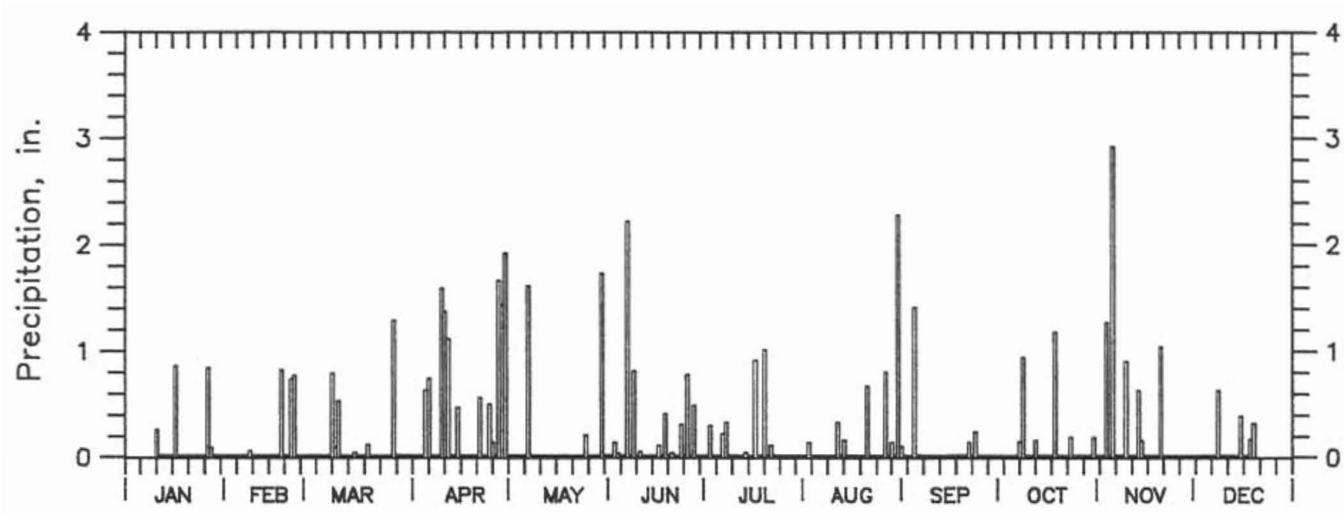


DRY FORK #1, 1994

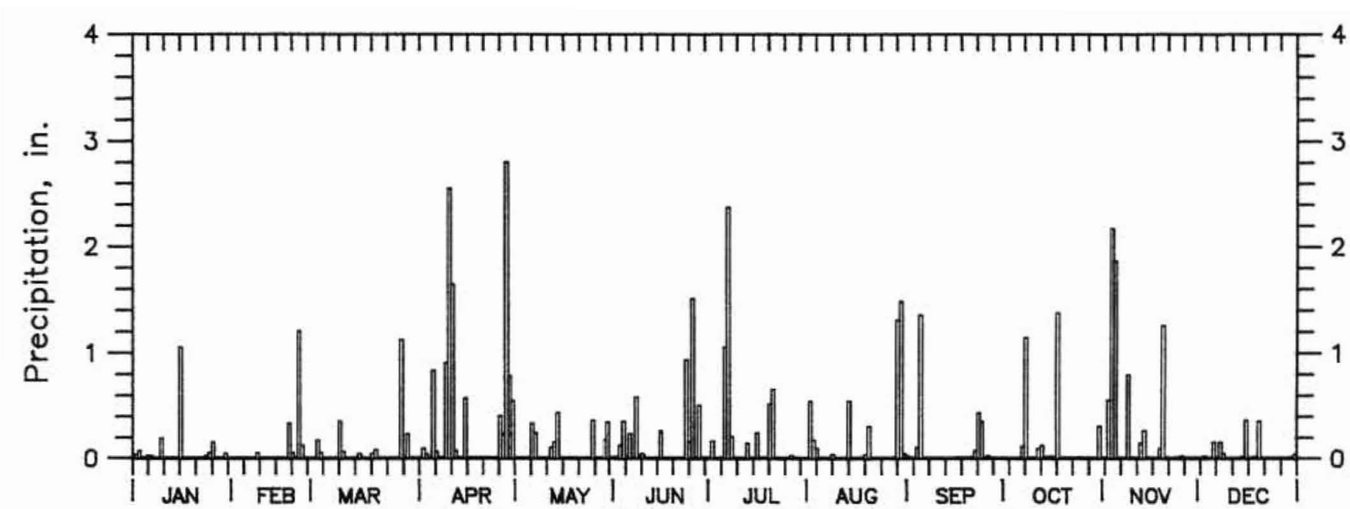
Figure 16. Bar graphs of daily precipitation for 1994 and 1995 for the precipitation stations used in this study.



SALEM, 1994

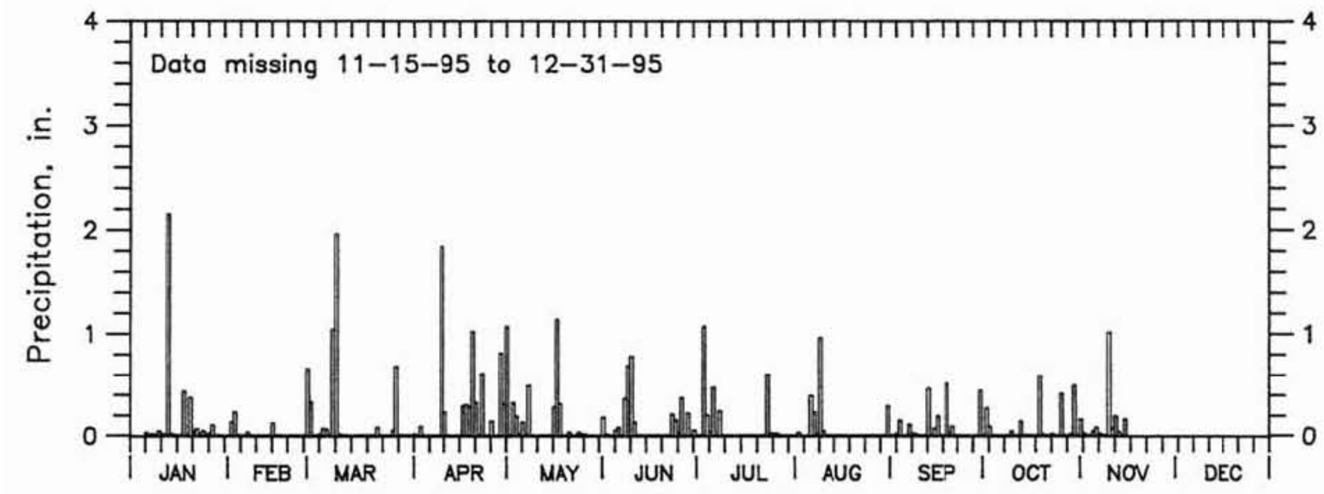


MONTAUK, 1994

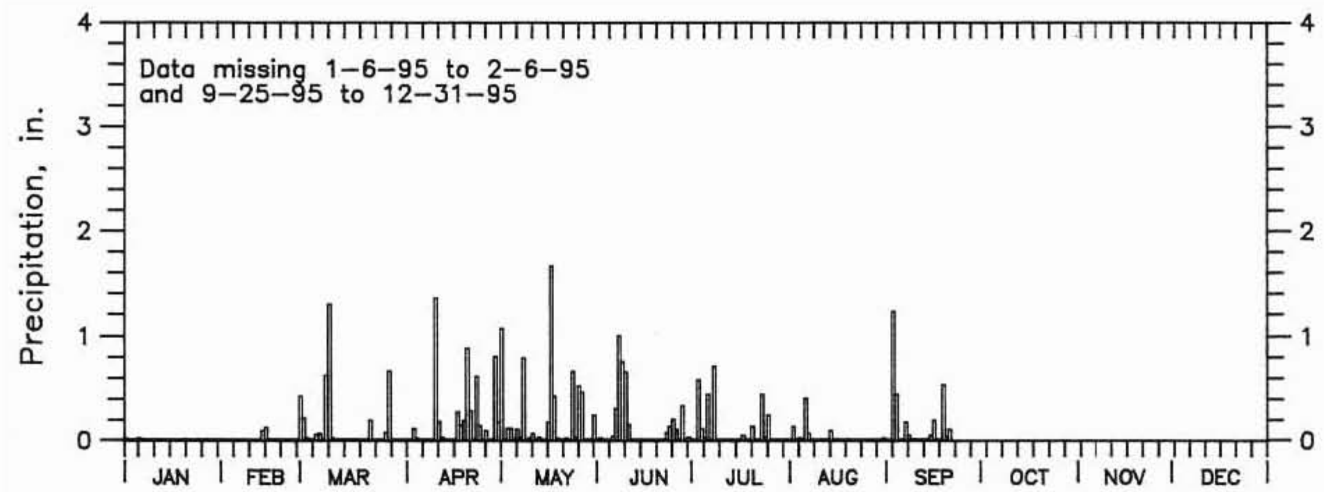


ROLLA - UMR, 1994

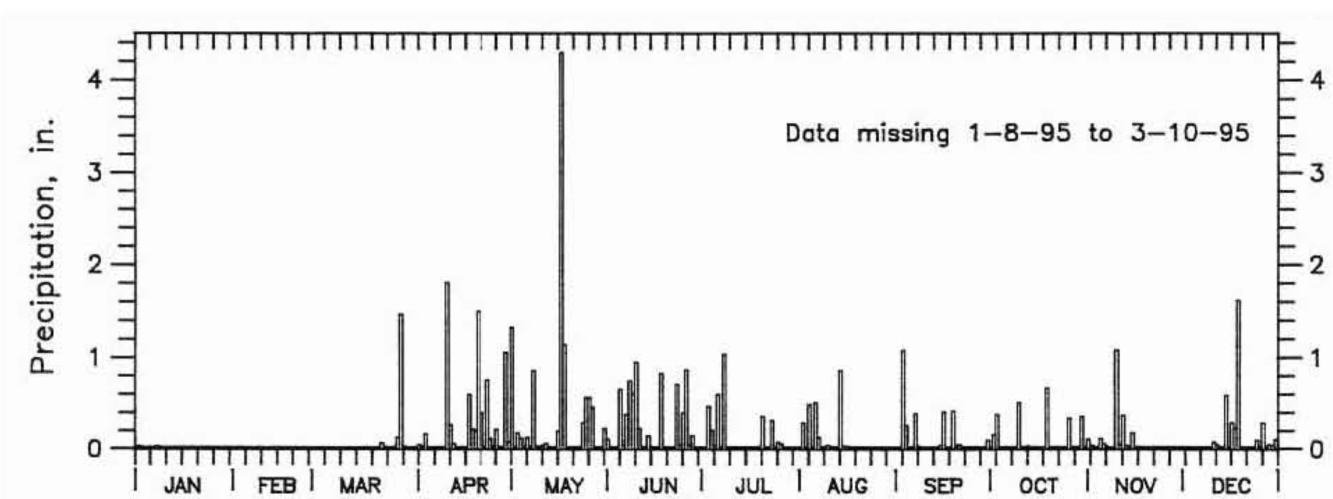
Figure 16 (continued)



DRY FORK #3, 1995

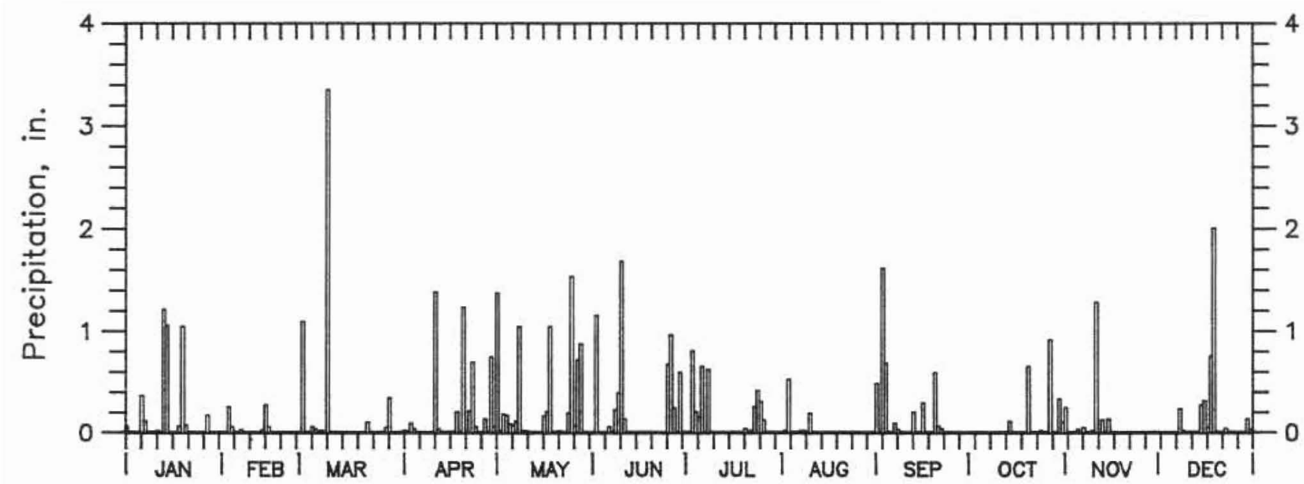


DRY FORK #2, 1995

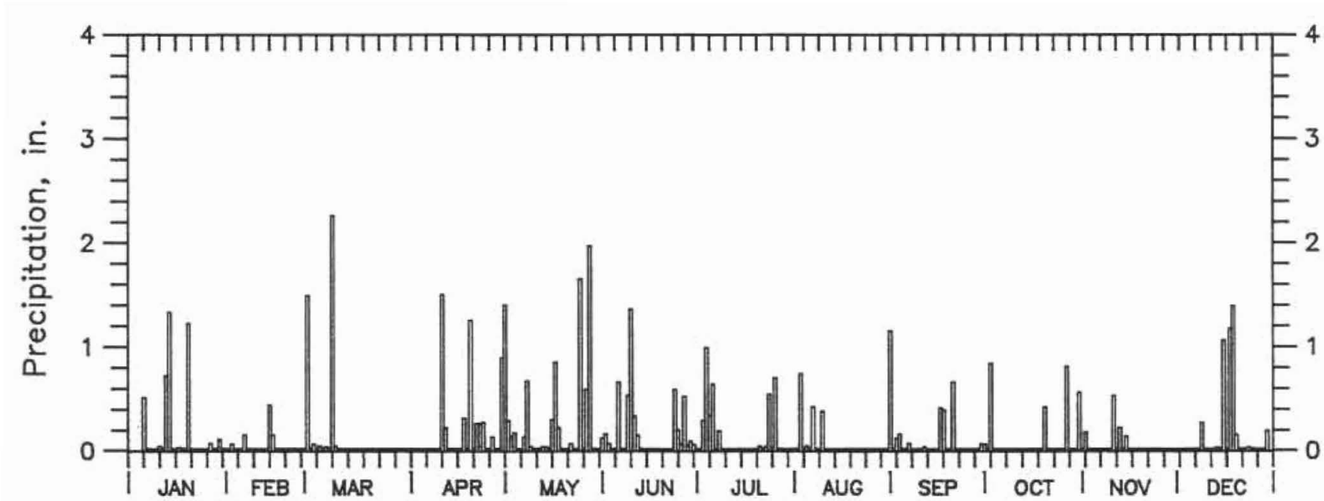


DRY FORK #1, 1995

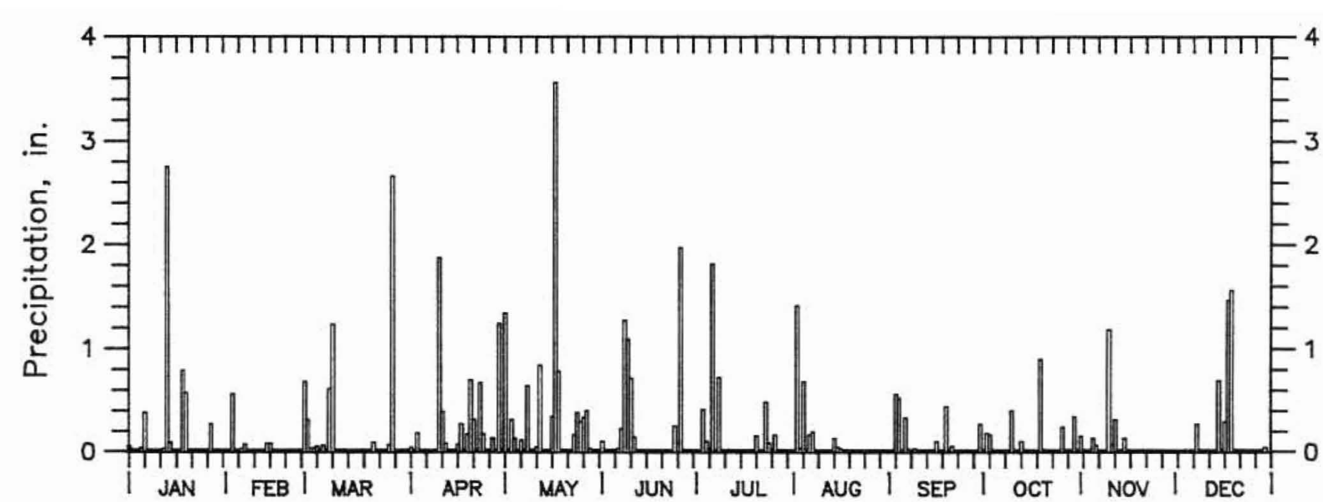
Figure 16 (continued)



SALEM, 1995



MONTAUK, 1995



ROLLA - UMR, 1995

Figure 16 (continued)

Annual Summary, 1994, Maramec Spring
Phelps County: NW 1/4 SE 1/4 SEC. 1, T. 37 N., R. 6 W.
37° 57' 20" north latitude, 91° 32' 57" west longitude
Land surface elevation: 774 feet above mean sea level. Measuring point is 773.97 ft msl
Recharge area: Approximately 310 square miles, 198400 acres. Note: *** Denotes missing data
Type of installation: Stevens digital water-stage recorder installed November 1985. Daily staff gage readings from 1965 to 1985.

AVERAGE DAILY DISCHARGE (CUBIC FEET PER SECOND), CALENDAR YEAR 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	159	186	221	229	***	222	224	185	159	130	115	134
2	159	178	207	213	***	214	215	183	156	130	116	133
3	159	168	193	204	***	213	210	184	155	127	116	128
4	157	166	185	196	338	213	204	180	152	127	121	127
5	156	165	174	198	328	212	201	175	160	127	229	126
6	155	162	167	249	318	207	197	175	160	127	295	126
7	155	159	179	272	310	207	343	173	152	127	230	127
8	151	159	212	262	300	207	373	169	152	127	193	127
9	149	157	213	250	290	208	324	166	151	127	224	127
10	148	154	210	742	279	205	278	166	148	126	278	127
11	148	154	201	***	265	201	247	166	148	126	236	127
12	148	152	193	***	260	195	233	165	144	126	197	124
13	148	151	189	***	255	194	229	162	145	126	174	125
14	148	148	186	***	250	199	229	171	144	125	162	125
15	145	148	183	374	348	206	207	163	144	125	162	125
16	144	148	172	365	340	204	205	162	142	125	162	126
17	144	149	173	354	315	205	208	162	140	125	159	132
18	141	151	184	343	294	204	209	159	136	125	153	135
19	139	152	190	331	272	202	208	159	135	127	150	131
20	138	156	190	318	256	198	204	159	135	125	148	128
21	137	160	187	306	245	198	246	159	135	126	262	127
22	139	246	183	296	237	198	253	159	135	125	248	127
23	146	378	183	288	231	199	232	156	134	123	211	127
24	176	354	176	275	230	200	224	154	134	121	186	125
25	233	325	171	264	230	199	217	152	134	119	167	125
26	255	292	199	257	224	214	212	152	133	119	161	125
27	285	258	356	252	212	214	205	152	132	119	159	125
28	298	236	336	281	207	299	201	152	129	119	153	125
29	268	—	303	***	205	284	194	150	129	118	144	125
30	232	—	264	***	242	240	191	152	130	117	141	125
31	206	—	243	—	247	—	186	172	—	118	—	125
MIN	137	148	167	196*	207*	194	186	150	129	117	115	124
MAX	298	378	356	742*	348*	299	373	185	160	130	295	135
AVG	173	193	207	297*	268*	212	229	164	142	124	182	127
Runoff:												
ac-ft	10643	10735	12740	14120*	14932*	12617	14100	10104	8495	7644	10814	7817
inches	0.64	0.65	0.77	0.85*	0.90*	0.76	0.85	0.61	0.51	0.46	0.65	0.47

1994 extremes: minimum - 115 (Nov. 1), maximum - 742 (Apr. 10), average - 186*
1994 total runoff: 134761* acre-feet, 8.15* watershed inches

Table 2. Average daily discharge, 1994, Maramec Spring.

Annual Summary, 1995, Maramec Spring
Phelps County: NW 1/4 SE 1/4 Sec. 1, T. 37 N., R. 6 W.
37° 57' 20" north latitude, 91° 32' 57" west longitude
Land surface elevation: 774 feet above mean sea level. Measuring point is 773.97 ft msl.
Recharge area: 310 square miles, 198400 acres
Type of installation: Stevens digital water-stage recorder installed November 1985. Daily staff gage readings from 1965 to 1985.

AVERAGE DAILY DISCHARGE (CUBIC FEET PER SECOND), CALENDAR YEAR 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	122	204	170	185	458	310	222	179	152	126	111	101
2	122	194	160	181	488	308	219	175	152	125	111	101
3	122	190	153	177	419	301	217	166	151	125	111	101
4	119	191	152	168	389	290	223	162	146	125	111	101
5	119	189	151	165	369	275	220	165	144	125	111	101
6	119	181	151	164	347	275	223	169	144	125	108	101
7	119	178	351	163	325	269	216	170	144	125	106	101
8	119	166	358	163	349	284	222	166	144	123	103	101
9	117	163	338	163	373	353	222	164	144	122	103	101
10	117	166	314	160	350	418	220	162	144	117	103	101
11	118	164	290	291	324	460	219	161	144	117	103	101
12	393	160	267	318	305	424	213	159	144	117	103	101
13	697	152	246	291	300	385	209	159	144	118	103	101
14	320	152	226	260	284	355	205	160	144	116	103	101
15	431	148	211	236	266	332	202	161	144	114	103	101
16	388	148	200	218	262	311	199	158	141	112	103	101
17	356	148	190	207	501	291	198	155	141	112	103	101
18	318	147	185	216	640	278	194	155	141	109	103	101
19	327	144	182	212	495	278	194	155	141	107	103	190
20	316	144	180	336	450	272	194	154	141	109	103	204
21	295	142	174	370	415	267	190	152	141	111	100	163
22	276	144	170	338	381	258	190	152	141	111	100	139
23	256	144	165	329	355	252	190	152	141	113	101	128
24	236	144	162	359	333	255	184	152	141	112	101	119
25	219	141	160	346	344	251	186	152	141	111	101	117
26	208	141	160	326	346	246	198	152	141	111	101	117
27	216	158	270	306	358	246	203	152	141	111	101	114
28	255	188	262	285	398	239	193	152	135	111	101	114
29	246	———	232	291	383	232	187	152	135	111	101	111
30	225	———	210	378	352	228	181	152	135	111	101	107
31	211	———	191	———	323	———	177	152	———	111	———	106
MIN	117	141	151	160	262	228	177	152	135	107	100	101
MAX	697	204	358	378	640	460	223	179	152	126	111	204
AVG	243	162	214	253	377	298	204	159	143	116	104	114
Runoff:												
ac-ft	14880	898	13152	15078	23171	17738	12516	9773	8493	7127	6180	7035
inches	0.90	0.54	0.80	0.91	1.40	1.07	0.76	0.59	0.51	0.43	0.37	0.43

1995 extremes: minimum - 100 (Nov. 21), maximum - 697 (Jan. 13), average - 199
1995 total runoff: 144130.9 acre-feet, 8.72 watershed inches

Table 3. Average daily discharge, 1995, Maramec Spring.

measure the electrical conductance of the spring water. Electrical conductance is proportional to the dissolved solids content of the water. As mineralization increases, conductance increases. Conductance is commonly used to detect changes in water chemistry. It does not, however, measure the content of specific ions. In this study, specific conductance was used to measure when the influx of water from a recharge event reached the spring. Rainfall has a very low dissolved solids content, and thus a low electrical conductivity. As soon as rainfall strikes the earth, the water begins dissolving minerals it comes in contact with. The process is slow enough, though, that it takes several weeks before the water approaches its maximum dissolved solids content. When fresh recharge reaches Maramec Spring, the specific conductance of the water begins to drop because the water contains less dissolved solids than water that was in the system prior to rainfall. The specific conductance was measured hourly, and the values stored by a data logger. Tables 4 and 5 show average daily specific conductivity values at Maramec Spring for 1994 and 1995. Figure 17 shows the instrument installation at Maramec Spring.

With the instrumentation described above, it was possible to correlate changes in spring flow with rainfall. It was also possible to determine to the nearest hour when the water from the recharge event arrived at Maramec Spring . Figures 18 and 19 show average daily discharge and average daily specific conductance at Maramec Spring, along with daily precipitation at Rolla-UMR for 1994 and 1995. The daily data clearly show a very fast response between precipitation and an increase in spring discharge, but that the water provided by the rainfall does not arrive at the spring until several days later, usually when the flow of the spring is declining or even approaching pre-storm discharge. A more detailed analysis of the Maramec Spring's response to precipitation using hourly data is presented later in this report.

Specific Conductance, 1994, Maramec Spring

Phelps County: NW 1/4 SE 1/4 Sec. 1, T. 37 N., R. 6 W.
37° 57' 20" north latitude, 91° 32' 57" west longitude
Land surface elevation: 774 feet above mean sea level. Note: *** Denotes missing data
Type of installation: Thor specific conductance transducer and data logger installed December, 1993, 1 year of data.

AVERAGE DAILY SPECIFIC CONDUCTANCE (MICROSIEMENS), CALENDAR YEAR 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	260	263	207	252	****	219	262	256	311	330	352	257
2	264	252	209	243	****	222	264	257	313	332	351	259
3	267	249	213	236	****	226	263	258	316	337	356	260
4	271	248	219	237	131*	230	262	260	329	342	351	262
5	275	250	222	239	134	235	260	262	323	340	351	263
6	278	251	225	242	135	237	258	264	323	337	352	266
7	280	253	227	245	139	236	242	266	324	343	352	268
8	284	253	231	247	146	236	235	268	324	340	348	270
9	287	255	235	248	150	240	248	270	325	341	345	274
10	290	258	239	242	155	244	245	273	323	343	343	278
11	292	261	242	228*	160	245	241	279	321	344	328	281
12	293	264	246	****	164	244	236	279	321	345	305	286
13	294	268	249	****	168	243	235	283	320	347	290	289
14	296	271	251	****	170	245	227	284	319	344	277	292
15	297	274	250	131*	178	246	226	288	319	344	265	295
16	299	278	248	138	188	244	229	291	317	345	264	297
17	300	282	249	142	192	244	232	296	315	346	262	303
18	303	285	250	143	197	244	236	299	316	346	261	306
19	306	286	252	148	199	245	241	299	319	348	261	309
20	309	289	252	154	195	247	246	300	317	351	260	310
21	310	293	254	161	191	249	245	303	317	353	264	312
22	312	293	255	168	191	252	251	304	316	353	268	314
23	314	299	257	174	194	254	255	304	318	355	265	313
24	316	284	259	182	197	256	256	306	319	355	263	316
25	319	271	262	188	198	259	258	305	320	355	261	321
26	322	253	262	192	202	259	256	306	322	357	258	325
27	324	235	269	197	204	264	258	307	323	350	258	327
28	324	217	270	192*	207	265	259	310	325	352	260	326
29	321	———	268	****	211	269	258	307	326	352	258	327
30	308	———	263	****	212	266	256	309	328	353	257	328
31	284	———	256	———	217	———	256	310	———	352	———	328

Table 4. Average daily specific conductance, 1994, Maramec Spring

Specific Conductance, 1995, Maramec Spring

Phelps County: NW 1/4 SE 1/4 Sec. 1, T. 37 N., R. 6 W.
37° 57' 20" north latitude, 91° 32' 57" west longitude
Land surface elevation: 774 feet above mean sea level. Note: *** Denotes missing data
Type of installation: Thor specific conductance transducer and data logger installed December, 1993, 2 years of data.

AVERAGE DAILY SPECIFIC CONDUCTANCE (MICROSIEMENS), CALANDAR YEAR 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	329	199	270	218	178	164	228	230	367	346	406	***
2	329	203	272	217	163	170	239	232	365	286	370	***
3	329	206	274	216	153	174	244	243	367	295	358	***
4	329	207	274	222	146	177	235	212	374	291	366	***
5	328	209	273	221	148	181	230	224	370	319	404	***
6	330	213	276	222	152	177	201	161	370	324	367	***
7	334	216	265	224	149	176	210	72	365	359	347	***
8	333	217	240	229	160	193	224	71	340	385	***	***
9	335	220	215	233	167	192	252	71	366	376	***	***
10	336	223	197	235	173	188	230	71	355	384	***	***
11	339	227	192	239	175	202	247	93	361	353	***	***
12	339	227	179	244	175	193	243	208	367	359	***	***
13	330	233	171	240	178	174	239	218	383	372	***	***
14	294	235	171	235	181	167	256	222	382	376	***	***
15	141	238	177	231	182	161	266	223	382	360	***	***
16	91	240	181	226	184	161	273	223	377	366	***	***
17	82	242	187	216	185	170	255	234	374	367	***	***
18	87	244	190	208	179	174	219	252	392	374	***	***
19	85	247	192	207	152	189	234	74	379	384	***	***
20	88	249	197	211	139	181	231	80	389	384	***	***
21	134	251	202	200	129	193	227	88	395	327	***	***
22	153	255	206	194	129	214	189	97	396	229	***	***
23	162	260	209	188	141	210	250	104	395	362	***	***
24	169	266	211	176	146	203	245	110	388	343	***	***
25	175	272	213	164	148	211	263	146	392	343	***	***
26	181	275	215	169	157	200	231	195	345	319	***	***
27	185	270	213	170	167	206	220	224	325	345	***	***
28	191	272	222	171	176	205	231	226	377	363	***	***
29	194	———	221	173	161	200	245	228	391	336	***	***
30	199	———	213	178	154	211	237	262	379	366	***	***
31	195	———	215	———	166	———	218	349	———	396	———	***

Table 5. Average daily specific conductance, 1995, Maramec Spring.

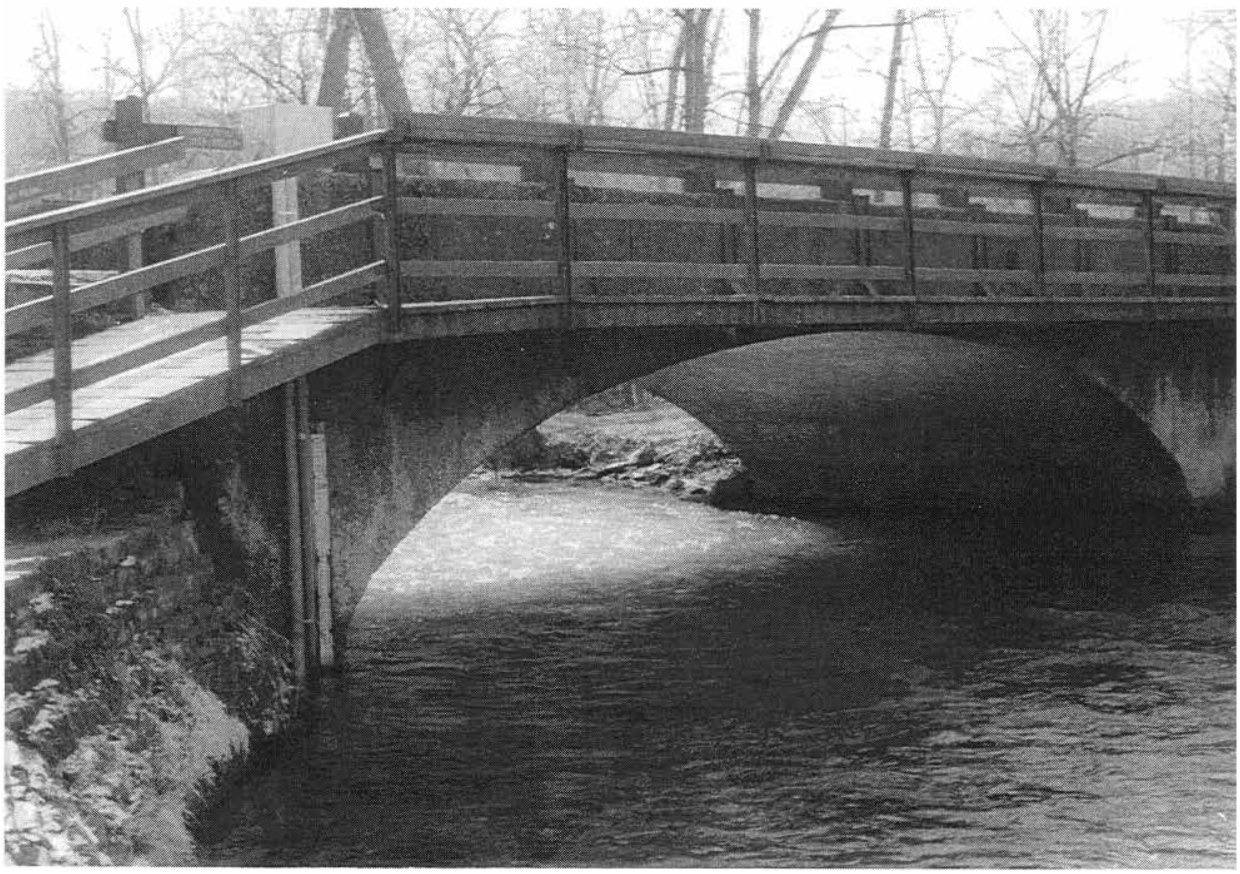


Figure 17. Photograph of gaging station installation at Maramec Spring. Photo by Jim Vandike.

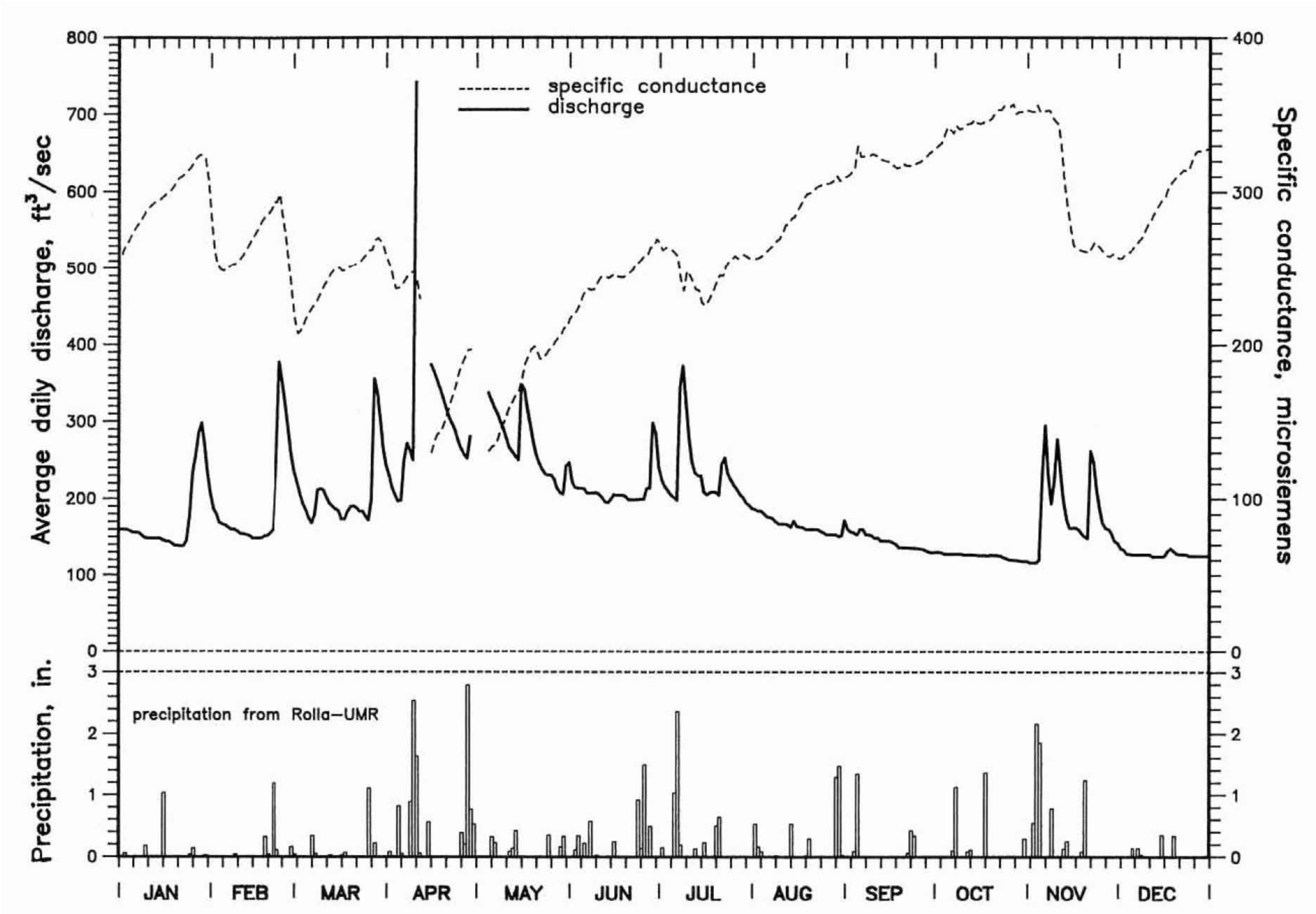


Figure 18. Average daily discharge and specific conductance at Maramec Spring, and daily precipitation at Rolla-UMR, 1994.

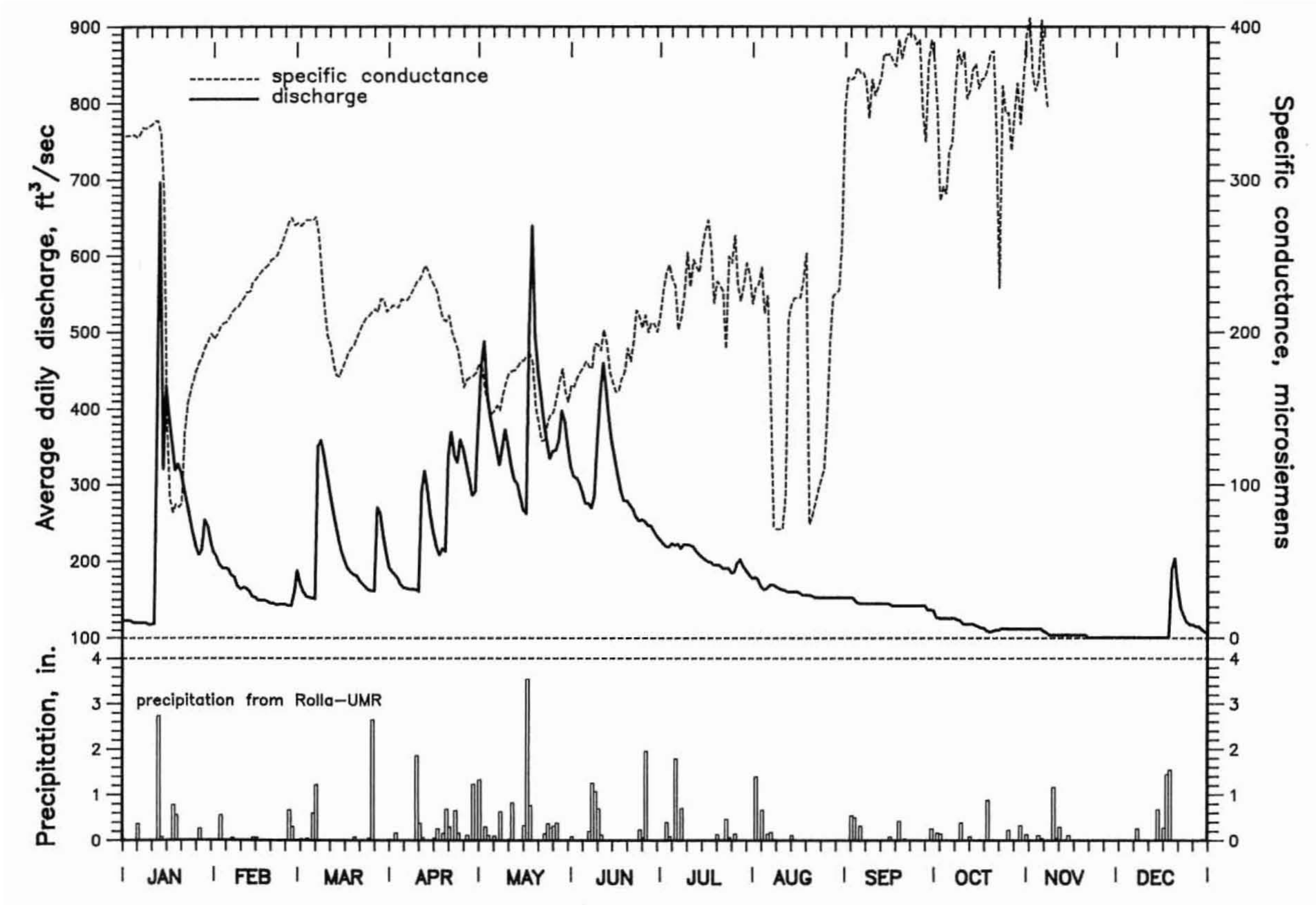


Figure 19. Average daily discharge and specific conductance at Maramec Spring, and daily precipitation at Rolla-UMR, 1995.

GROUNDWATER TRACING

Delineating losing streams is a first step in determining the potential recharge area for a spring, but it does not establish which areas provide recharge to which spring. Fluorescent dyes are routinely used to physically link water disappearing underground through the base of a sinkhole or losing stream to the spring where it emerges. The mechanics of conducting a dye trace are fairly simple. Dye is added to water that is entering the subsurface through a losing stream or sinkhole, and springs in the area are monitored to see where the dye reappears. Sometimes, the most difficult step is finding a place where dye can be placed that it can be taken directly into the subsurface. Sinkholes can be good dye injection sites, but are typically dry; they either require hauling water by tank truck, or waiting for a storm and injecting the dye when runoff is flowing into the sinkhole. Losing streams generally prove to be more successful dye injection sites. As with sinkholes, sometimes the only way to inject the dye is to wait until sufficient rainfall has occurred, and there is runoff entering the creek that flows underground downstream of the dye injection point. In many cases it is possible to locate a small spring or seep either along the reach of a losing stream, or in a small tributary valley which flows into it, that provides enough water to carry the dye underground.

Fluorescent dyes are routinely used for groundwater tracing. There are many commercially available fluorescent dyes, but only a few are well suited for this purpose. To be suitable for groundwater tracing, the dyes must, of course, be soluble in water and be environmentally safe. They must be detectible in very low concentrations, and not be readily absorbed by the earth materials they come in contact with. Two dyes which have all of these characteristics and have been widely used for many years for groundwater tracing are fluorescein (also known as uranine C) and Rhodamine WT. Both of these dyes were used in groundwater tracing in the Maramec Spring area. They are very colorful and visible to the unaided eye in concentrations lower than 1 mg/L. Their colorful nature, however, is not what makes them so well suited for groundwater tracing. Fluorescent substances, when illuminated at a particular light wavelength, give off light at a slightly different wavelength. For example, fluorescein has peak excitation and emission wavelengths of about 500 nanometers (nm) and 517 nm, respectively. In other words, when fluorescein dye is illuminated with light at a wavelength of 500 nm, it gives off light at a wavelength of 517 nm. Rhodamine WT is quite similar, except for its excitation and emission wavelengths are about 550 nm and 567 nm, respectively.

As previously mentioned, both of these dyes can be detected visually in concentrations of about 1 mg/L. However, using the proper instruments, both of the dyes can be detected at levels well below 1 microgram per liter (µg/L). The fluorescence allows them to be detected in very low concentrations using an instrument called a spectro-

fluorophotometer. The spectrofluorophotometer consists of an adjustable wavelength light source, and a corresponding adjustable wavelength light detector. The samples to be analyzed for dye are placed into the instrument. The instrument illuminates the sample, beginning at an excitation wavelength of 475 nm and an emission wavelength 17 nm higher, 492 nm. The 17 nm spacing is held constant while the sample is scanned. The scan ends at an excitation wavelength of 575 nm and an emission wavelength of 592 nm. If fluorescein dye is present, the graphed results show an emission peak at about 517 nm; for Rhodamine the emission peak is about 567 nm. Peak height is proportional to the amount of dye present. Samples containing neither fluorescein or Rhodamine WT show a gently decreasing fluorescence throughout the scan. Since the peak wavelengths of the two dyes are separated by about 50 nm, both can be used simultaneously. So using both dyes, it is possible to conduct dye traces from two injection sites to the same spring without causing interference (figure 20).

Since the dyes can be detected in minute concentrations, fairly small quantities of dye can be used. Seldom is it necessary to use more than a few pounds of dye, even where the dye may travel several miles underground to recharge a spring that is discharging many million gallons of water per day. It is not practical to visually monitor each spring or gaining-stream reach that may receive dye, nor collect water samples from them on a frequent basis. It may take several weeks for dye to travel from injection to recovery points, and the dye concentration will likely be below the visual threshold. So, packets of activated carbon are placed in springs and gaining streams to capture the dyes should they be present in the water. The packets are replaced at regular intervals, and returned to the laboratory where they are analyzed for dye. In the laboratory, the packets are cleaned under a high-speed water jet to remove sediment and algae, and the cleaned carbon granules are placed into specimen cups. About 20 ml of a 5 percent solution of ammonium hydroxide in ethyl alcohol is added to the specimen cups to release the dye from the activated carbon. The carbon packets allow the springs to be monitored continuously; the activated carbon is capable of adsorbing dye for several weeks. The packets are normally changed at one to two-week intervals.

Although Maramec Spring is the primary focus of this study, other springs were also monitored for dye. In addition, activated carbon packets were placed in several gaining streams to monitor for possible dye presence. Table 6 shows the names of springs and gaining streams that were monitored; their locations are shown on figure 21.

There have been five successful dye traces linking Maramec Spring to its recharge area as well as other traces that show the areas providing recharge to springs in adjacent watersheds. Some of these traces were conducted several years ago in conjunction with other studies. Each of the dye traces conducted during this study will be discussed in the following paragraphs, along with the two traces to Maramec Spring that were conducted during previous studies. Figures 22 and 24 shows the injection and recovery locations for dye traces discussed in this report. Table 7 summarizes the dye trace data. The straight lines used to depict the traces on the map are not meant to imply that groundwater follows a straight line from where the dye was injected to where it was recovered. It is unlikely that the dye followed a straight path, but without additional information to prove otherwise the straight-line interpretation is the simplest to depict graphically.

Asher Hollow Trace

Asher Hollow is a Meramec River tributary that drains an 11.4 mi^2 area immediately south of Maramec Spring. Both Asher Hollow and its tributary to the west,

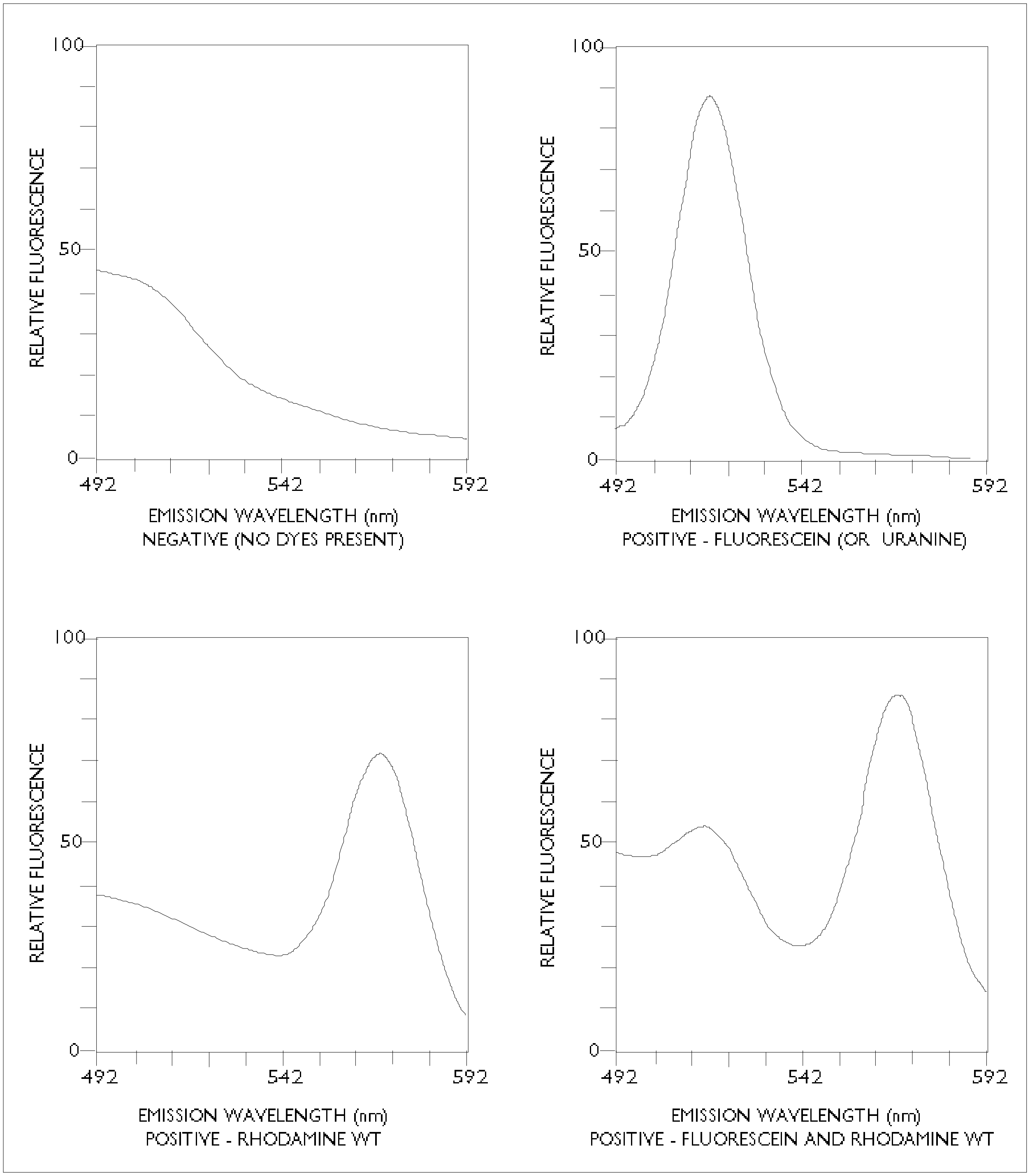


Figure 20. Typical spectrofluorograms of carbon samples containing no dye, fluorescein dye, Rhodamine WT dye, and both fluorescein and Rhodamine WT dye.

Map Number	Dye Monitoring Site Name	Location
1	Maramec Spring	NE 1/4, NW 1/4, SE 1/4, Sec. 1, T. 37 N., R. 6 W
2	Dry Fork at Mo. Hwy. 8-68	NW 1/4, SW 1/4, SW 1/4, Sec. 34, T. 38 N., R. 6 W.
3	Meramec River at Mo. Hwy. 8	NW 1/4, SE 1/4, SE 1/4, Sec. 6, T. 37 N., R. 5 W.
4	Benton Creek near mouth	NE 1/4, NE1/4, NW 1/4, Sec. 32, T. 37 N., R. 5 W.
5	Dry Fork at Phelps Co. Rt. F	SE 1/4, SE 1/4, SW 1/4, Sec. 22, T. 37 N., R. 7 W.
6	Lane Spring	SE 1/4, SW 1/4, NW 1/4, Sec. 32, T. 36 N., R. 8 W.
7	Little Piney Creek upstream of Lane Spring	SE 1/4, SW 1/4, NW 1/4, Sec. 32, T. 36 N., R. 8 W.
8	Finn Spring	NW 1/4, NW 1/4, SE 1/4, Sec. 4, T. 35 N., R. 8 W.
9	Little Piney Creek downstream of Piney and Finn springs	NE 1/4, NE 1/4, SW 1/4, Sec. 4, T. 35 N., R. 8 W.
10	Piney Spring	SW 1/4, SW 1/4, SE 1/4, Sec. 4, T. 35 N., R. 8 W.
11	Relfe Spring	NW 1/4, NE 1/4, SE 1/4, Sec. 36, T. 35 N., R. 10 W.
12	Dry Fork 2 miles upstream of Mo. Hwy 72	SW 1/4, SW 1/4, N 1/2, Sec. 6, T. 34 N., R. 6 W.
13	Barnitz Prong at Dent County Rt. H	SW 1/4, SW 1/4, NE 1/4, Sec. 21, T. 34 N., R. 7 W.
14	Skiles Spring	NE 1/4, SE 1/4, NE 1/4, Sec. 29, T. 34 N., R. 7 W.
15	Barnitz Prong upstream of Skiles Spring	NE 1/4, SE 1/4, NE 1/4, Sec. 29, T. 34 N., R. 7 W.
16	Montauk Spring	SE 1/4, SE 1/4, NE 1/4, Sec. 22, T. 32 N., R. 7 W.
17	Shaffer Spring	NE 1/4, SE 1/4, SW 1/4, Sec. 20, T. 32 N., R. 6 W.
18	Parker Hollow near mouth	SE 1/4, SE 1/4, SW 1/4, Sec. 29, T. 32 N., R. 6 W.
19	Welch Spring	SE 1/4, SE 1/4, SE 1/4, Sec. 10, T. 31 N., R. 6 W.

Table 6. Names and locations of springs and streams monitored for dye.

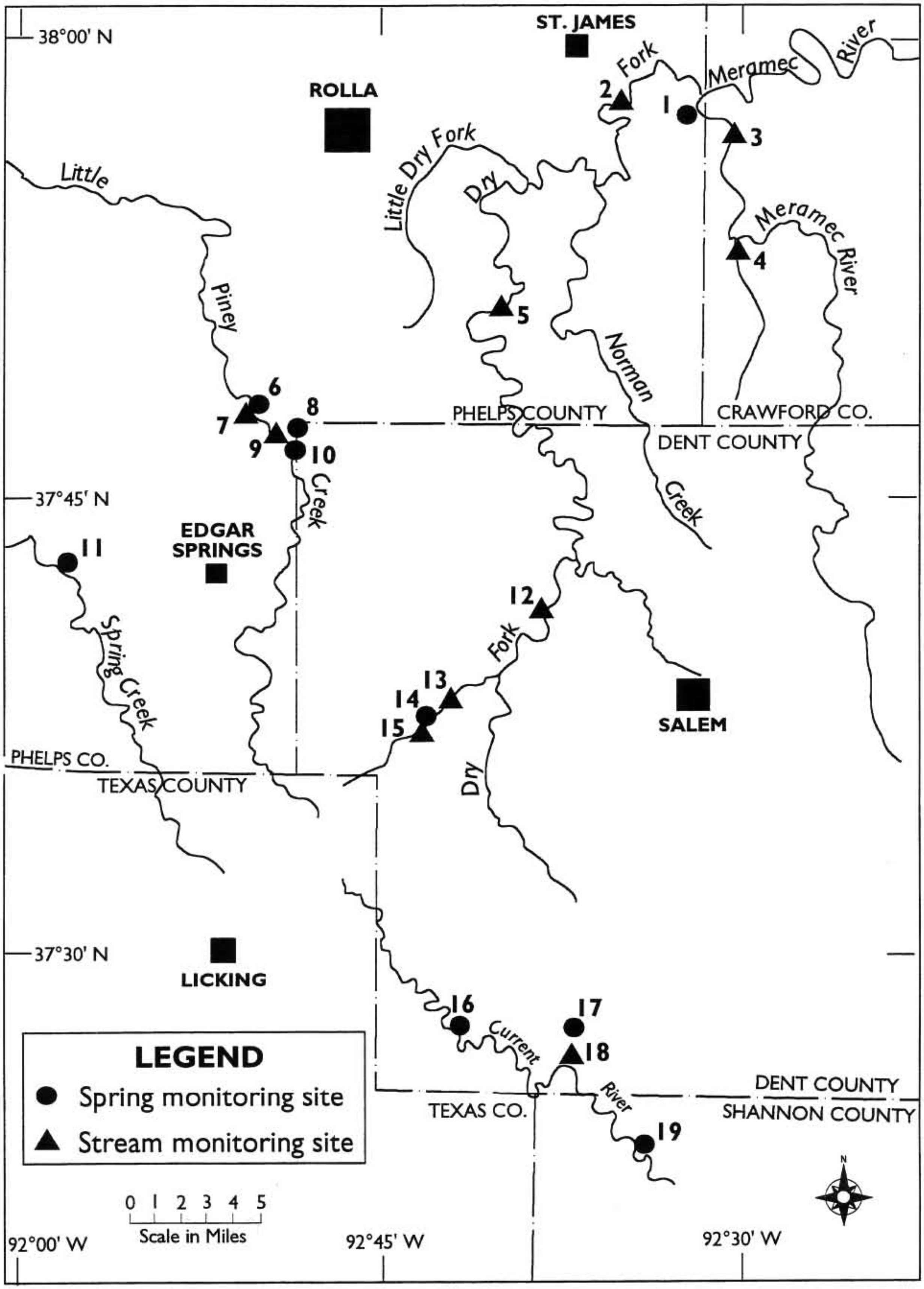


Figure 21. Dye monitoring sites during study.

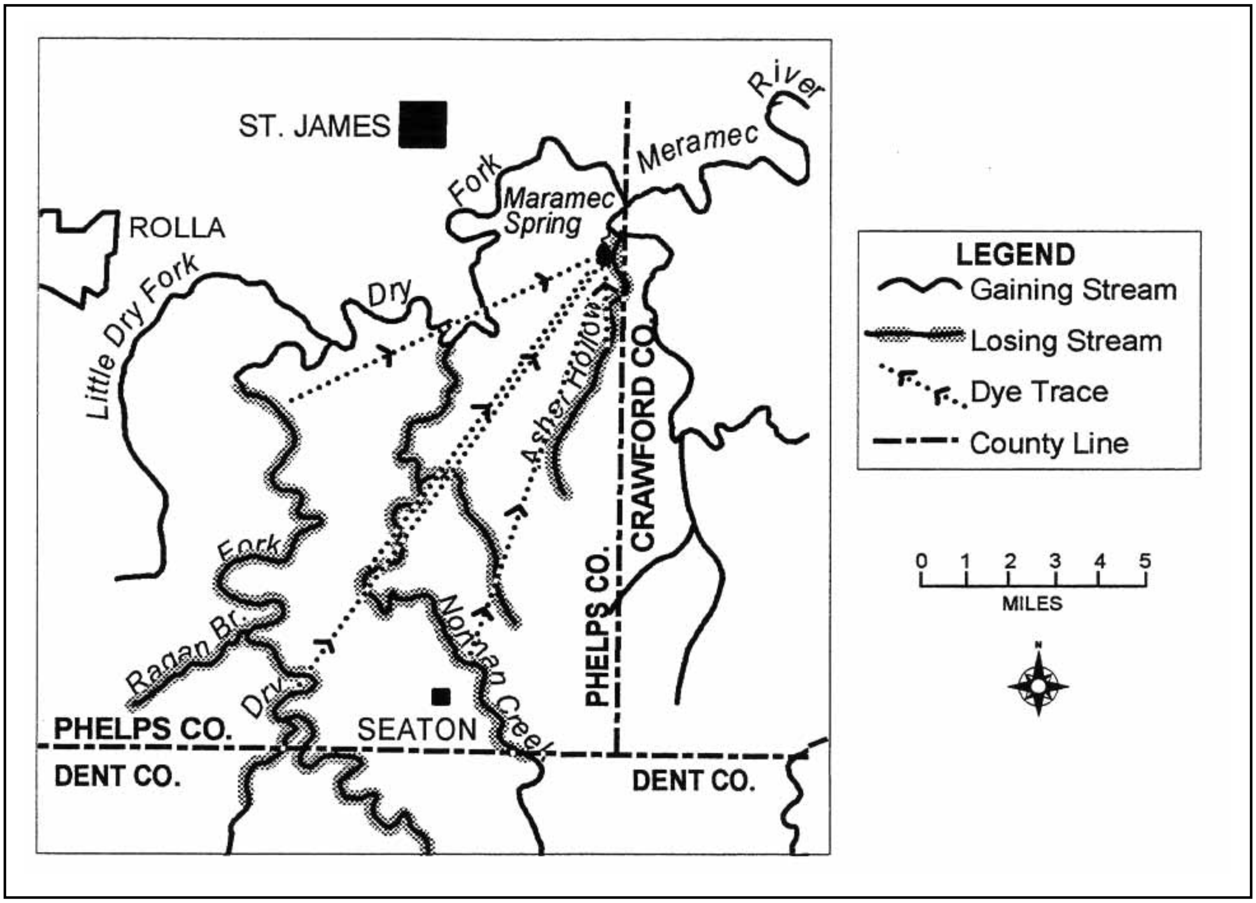


Figure 22. Map showing successful dye traces to Maramec Spring.

Reference Number	Injection Site Name	County	Location (Q-Sec-Twn-Rng) (Long[N]-Lat[W])	Dye Type and Amount	Injection Date	Recovery Site Name and Time	County	Location (Q-Sec-Twn-Rng) (Long[N]-Lat[W])	First Recovery interval from-to
01	Asher Hollow	Phelps	SE S13 T37N R6W 37.55.22-91.31.54	fluorescein 1 lb	Feb. 16, 1994 1530 hours	Maramec Spring	Phelps	SE S1 T37N R6W 37.57.13-91.31.58	Feb. 15, 1994 Feb. 23, 1994
02	Dry Fork Trib. near Rt. F	Phelps	NE S26 T37N R7W	Rhodamine 37.54.10-91.39.36	Mar. 26, 1994 WT, 9 lbs	Maramec Spring 1600 hours	Phelps	SE S1 T37N R6W 37.57.13-91.31.58	Apr. 1, 1994 Apr. 7, 1994
03	Upper Norman Creek	Phelps	SW S21 T36N R6W	fluorescein 37.49.26-91.35.43	Aug. 3, 1994 6lbs	Maramec Spring 1600 hours	Phelps	SE S1 T37N R6W 37.57.13-91.31.58	Aug. 15, 1994 Aug. 24, 1994
04	Upper Little Piney Creek	Phelp	SE S8 T34N R8W	fluorescein 37.39.35-91.49.47	Oct. 4, 1994 5lbs	Relfe Spring 1400 hours	Phelps	SE S36 T35N R10W 37.42.48-91.58.33	Oct. 4, 1994 Dec. 6, 1994
05	Dry Fork at pipeline leak	Phelps	NW S35 T36N R7W	Rhodamine 37.48.16-91.40.18	May 13, 1982 WT, 27 lbs	Maramec Spring 1030 hours	Phelps	SE S1 T37N R6W 37.57.13-91.31.58	May 25, 1982 May 26, 1982
06	Norman Creek (USGS)	Phelps	SE S7 T36N R6W	Rhodamine 37.51.07-91.37.09	Aug. 23, 1972 WT. 9 lbs.	Maramec Spring 1400 hours	Phelps	SE S1 T37N R6W 37.57.13-91.31.58	Oct. 30, 1972 Nov. 6, 1972

Reference Number	Injection Site Name	Injection Elevation (ft-msl)	Recovery Site Name	Recovery Elevation (ft-msl)	Straight Line Distance (mi)	Travel Time (Days) Min	Travel Time (Days) Max	Slope (ft/mi)	Velocity (mi/day) Min	Velocity (mi/day) Max
01	Asher Hollow	870	Maramec Spring	785	2.12	7	7	40.1	0.30	2.12
02	Dry Fork Trib near Rt F	1030	Maramec Spring	785	7.81	6	12	31.4	0.65	1.30
03	Upper Norman Creek	995	Maramec Spring	785	9.63	12	21	9.63	0.46	0.80
04	Upper Little Piney Creek	1065	Relfe Spring	835	8.52	1	63	27.0	0.14	*****
05	Dry Fork at pipeline leak site	955	Maramec Spring	785	12.8	12	13	13.3	0.98	1.07
06	Norman Creek (USGS)	930	Maramec Spring	785	8.7	69	76	16.7	0.11	0.13

Table 7. Physical data for dye traces in the Maramec Spring area.

Brown Hollow, are losing streams essentially from headwaters to mouth.

Both Asher Hollow and Brown Hollow are normally dry, but there is private lake on a small tributary of Asher Hollow about 2 miles south of Maramec Spring whose overflow and leakage reaches the channel of Asher Hollow, and then flows underground. On February 16, 1994, one pound of fluorescein was added to the water leaking from the lake which flowed into Asher Hollow in the SE 1/4 Sec. 13, T. 37 N., R. 6 W. Approximately 10 gpm was flowing into Asher Hollow, but flow disappeared into the subsurface within a few feet. The creek bed here consists of coarse gravel and pinnacles of weathered Gasconade Dolomite.

The dye reappeared at Maramec Spring between February 16 and February 23, 1994, less than one week after it was injected. It was detectable at the spring until about April 1, 1994, or about 6 weeks.

Hoffman Farm Trace

Dry Fork is generally considered to be a gaining stream downstream from about Phelps County Route F. For about a mile upstream from Route F, Dry Fork typically consists of a series of long pools that may or may not have flow between them. Groundwater-level measurements in this area show the potentiometric surface to be relatively deep, and below streambed elevation of Dry Fork. This indicates that the pools in Dry Fork for some distance above Route F may not represent water-table elevation, but may instead be water perched on fine-grained alluvial materials. Small tributary watersheds draining the area immediately south of Route F and east of Dry Fork are developed in Roubidoux Formation, and are losing streams.

On March 26, 1994, 9 lbs of Rhodamine WT (20%) was introduced into the bed of a small Dry Fork tributary about 1/4 mile south of Route F and 1/2 mile east of Dry Fork in the NE 1/4 Sec. 26, T. 37 N, R. 7 W. Runoff from a brief, heavy rainstorm was flowing through the drainage toward Dry Fork. An estimated 200 gpm was entering the subsurface at and immediately downstream of the dye injection site. The site was revisited two days later; there was no sign of the dye, and the channel was dry. Leaves and other debris in the channel downstream of where dye was injected showed that runoff from the storm did not reach the eastern edge of the Dry Fork floodplain.

The dye began appearing at Maramec Spring 7.8 miles to the northeast between 6 and 12 days after injection. This was a period of extremely wet weather, and the rate of groundwater recharge was very high. This moved the dye through the conduit system quickly, and dye was detectible at Maramec Spring for only about 4 weeks.

Upper Norman Creek Trace

Norman Creek, Dry Fork's largest tributary, drains about a 52 mi^2 area along the eastern side of Dry Fork watershed. The stream rises near the village of Howes about four miles north of Salem, and it intersects with Dry Fork about four miles southwest of Maramec Spring.

Norman Creek is a losing stream throughout most of its length. Upstream from Route JJ near Seaton, short reaches of Norman Creek display gaining-stream characteristics, and there is normally some flow in this area. Downstream from here to its mouth, a straight-line distance of about 7 miles, the creek is almost always dry. Figure 23 shows Norman Creek at Phelps County Route F, about two miles upstream from its mouth. Upstream from Route F Norman Creek drains about 48 mi^2.

During dry weather, the terminal water-loss zone may migrate upstream several miles south of the Phelps-Dent County line as subsurface drainage lowers the water table elevation in the transition area between gaining and losing conditions. In wet weather there may be some flow through

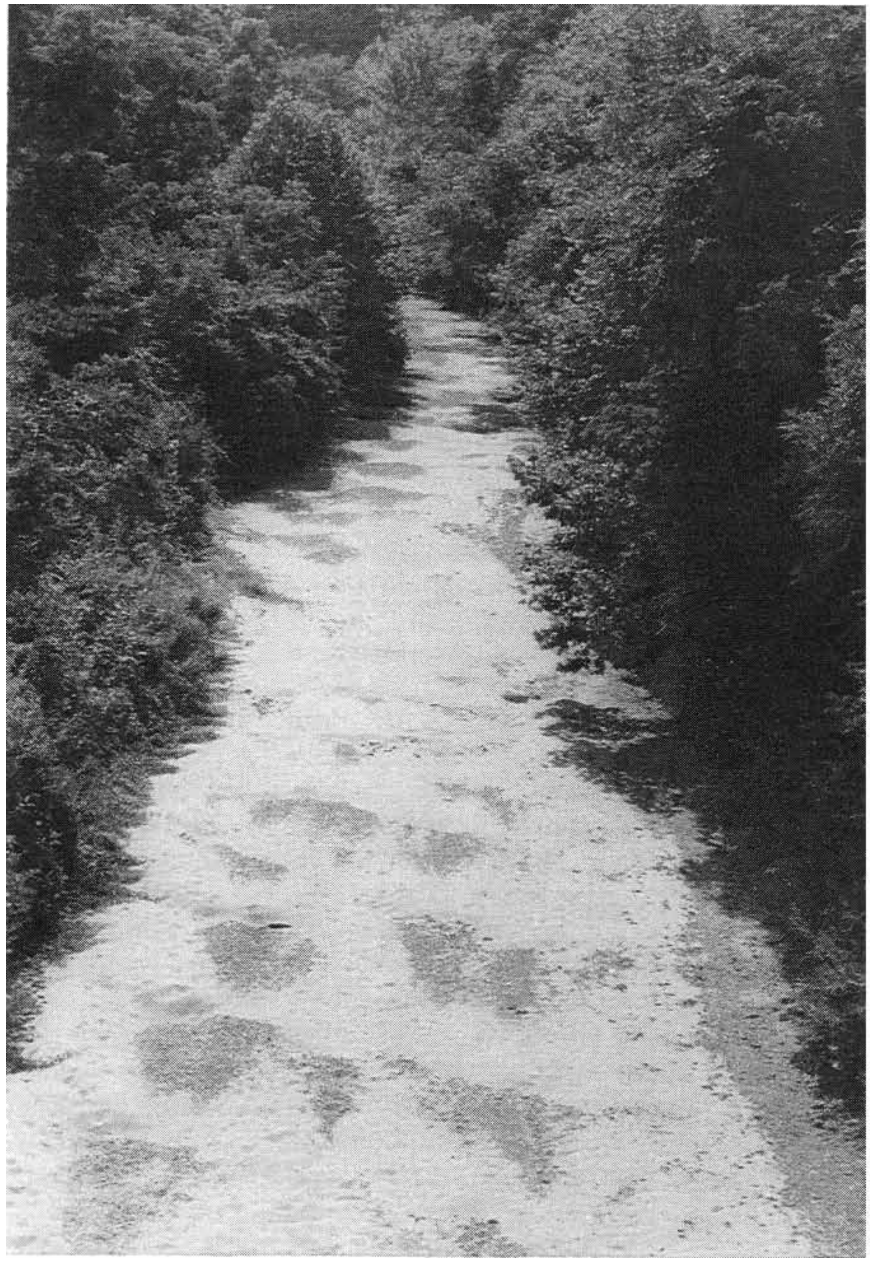


Figure 23. Norman Creek at Phelps County Route F. Photo by Jim Vandike.

the dry reach, but only after intense or prolonged rainfall is there flow throughout the entire length of Norman Creek.

On August 3, 1994, 6 lbs of fluorescein was introduced into the channel of Norman Creek on the Johnie Shoemate farm about a mile northeast of Seaton in the SW 1/4 Sec. 21, T. 36 N., R. 6 W. There was flow in Norman Creek upstream from this point for several miles, but downstream there was no flow from the injection site to the mouth of the creek. At the injection site, a flow of about 30 gpm was disappearing into creek bed at a small pool. Twenty four hours later, some dye was still present in the terminal pool, but most of it had been washed into the subsurface.

The dye reappeared at Maramec Spring, 9.5 miles to the northeast, between August 15 and August 24, between 12 and 21 days after injection. This trace was initiated during a relatively dry period, and dye continued to be detectible at Maramec Spring until the about October 13, 1994.

Little Piney Creek Trace

Little Piney Creek is a Gasconade River tributary that drains the area immediately west of Dry Fork watershed. Through the lower half of its length, Little Piney is a gaining stream and has a well sustained base flow provided by several second and third magnitude springs. Perennial flow begins about two miles upstream from the U.S. Highway 63 bridge where the flows of Piney and Finn springs flow into the Little Piney. There is commonly some flow for a short distance upstream from here, but from about mile south of Piney Spring to its headwaters in northern Texas County, Little Piney Creek is a losing stream. The losing-stream reach of the Little Piney drains an area of about 70 mi^2. The only notable gaining stream in upper Little Piney Creek watershed is Black Oak Creek, which drains an 8.5 mi^2 area northwest of the village of Lennox. Black Oak Creek appears to maintain its flow or increase in flow from near its headwaters to a short distance upstream from its confluence with Little Piney Creek three miles southeast of Edgar Springs, where its flow loses into the subsurface.

There is another short segment of upper Little Piney Creek about 3.5 miles southeast of Edgar Springs where there is typically a small amount of flow in the channel. On October 4, 1994, 5 pounds of fluorescein dye was introduced into the channel of Little Piney Creek where flow in this zone enters the subsurface in the SE 1/4 Sec. 8, T. 34 N., R. 8 W. There was no flow in the creek for several miles downstream.

The dye was recovered at Relfe Spring, nearly 9 miles northwest of the injection site. Relfe Spring rises along Spring Creek, a Big Piney River tributary. Relfe Spring was not being monitored for dye at the onset of this study. When dye failed to appear at any of the other sampling sites, samples were collected at Relfe Spring. Very high fluorescein levels were detected during the first sampling period, December 1 to December 6, 1994. Dye continued to be detectible until about February 17, 1996 (figure 24).

Although it is almost certain that the source of the dye recovered at Relfe Spring was from the Little Piney Creek trace, the trace should eventually be repeated for verification. Relfe Spring was not being monitored when the dye was injected, and no background fluorescent data had been collected.

Upper Dry Fork Dye Injection

Two additional dye traces were attempted during this study which were inconclusive. On October 19, 1994, 9 lbs of Rhodamine WT (20%) dye was injected into the channel of Dry Fork directly beneath the Missouri Highway 32 bridge southwest of Salem in the NW 1/4 Sec. 11, T. 33 N., R. 7 W. The entire flow of the creek, approximately 10 gpm, was disappearing into the streambed a few feet downstream of where the dye was placed. The dye was not recovered at any of the sampling sites.

Kissock Creek Dye Injection

Kissock Creek is a small tributary of Barnitz Prong that drains about 8 mi^2 in the southwestern part of Dry Fork basin. Barnitz Prong is a gaining stream from headwaters to mouth, but Kissock Creek is a losing stream throughout most of its length.

On June 25, 1995, 10 lbs of fluorescein dye was injected into a small tributary of Kissock Creek in the White River Trace Wildlife Area in the SE 1/4 Sec. 32, T. 34 N., R. 7 W. About 5 to 10 gpm was flowing in the branch, provided by small seeps and springs just upstream of the injection site. Flow in the creek ended less than 100 ft downstream of the injection site at a pool, and the channel was dry from there to its confluence with Kissock Creek; Kissock Creek was dry for at least another mile downstream.

A small quantity of dye from this trace was recovered at the monitoring points on Barnitz Prong a short distance downstream

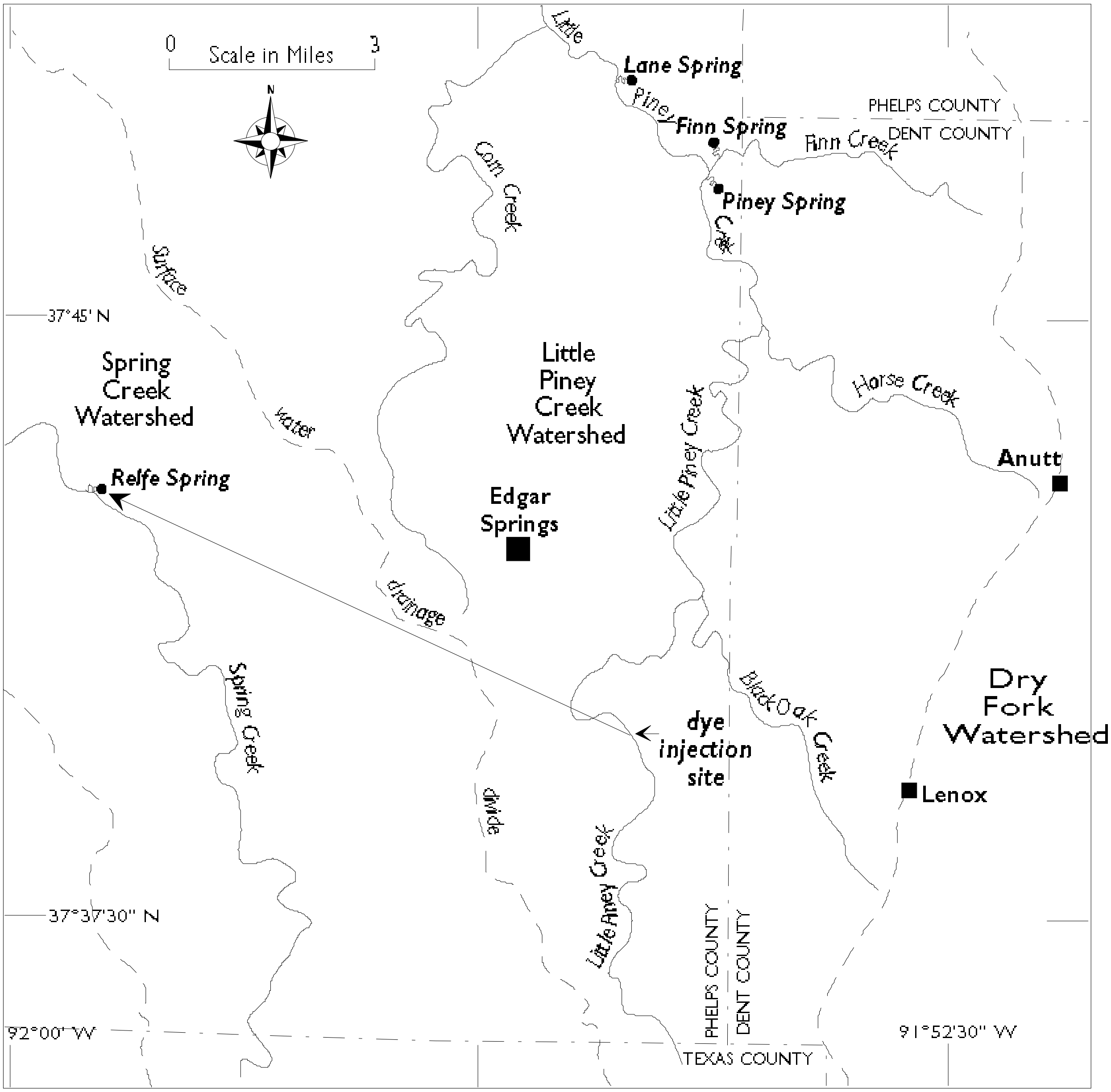


Figure 24. Map showing injection and recovery sites, Piney Creek trace.

from the injection site. Dye was likely transported to these by surface flow, the result of runoff from a rainstorm which occurred several days after the dye was injected. Based on the quantity of dye detected, only a small amount of the dye was washed downstream. The remainder of the dye was not recovered at any of the other monitoring points.

Norman Creek Trace

Two dye traces to Maramec Spring were conducted during previous studies. On August 23, 1972, following a 2-inch rain, one gallon of Rhodamine WT was poured into the dry streambed of Norman Creek in the SE 1/4 Sec. 7, T. 36 N., R. 6 W. in front of a slug of runoff traveling down Norman Creek. The discharge of Norman

Creek was estimated to be about 10 ft^3/sec. The dye reappeared at Maramec Spring, 8.7 miles to the northeast, between 68 and 75 days after injection (Gann and Harvey, 1975).

Williams Pipeline Trace

In November 1981, a pipeline transporting ammonium nitrate and urea fertilizer developed a leak near where it crosses Dry Fork about a mile north of the Dent-Phelps County line. A week later, Maramec Spring began experiencing the worst water-quality problems that have ever occurred in the recorded history of the Spring. Although there was little doubt that the cause of the elevated nitrate and ammonia and low dissolved oxygen at Maramec Spring was the pipeline leak, a dye trace was conducted to prove the hydrologic link between the two sites.

On May 13, 1982, three gallons of Rhodamine WT was introduced into the unnamed tributary of Dry Fork where the pipeline leak occurred in the NE 1/4 Sec. 35, T. 36 N., R. 7 W. (figure 25). The dye was carried downstream into Dry Fork a few hundred feet to the east. For the next mile downstream, Dry Fork consisted of several pools connected by flow. Downstream from the pools there was no flow for the next several miles. The dye reappeared at Maramec Spring, 12.8 miles to the northeast, between 11 and 12 days after it was injected (Vandike, 1985).

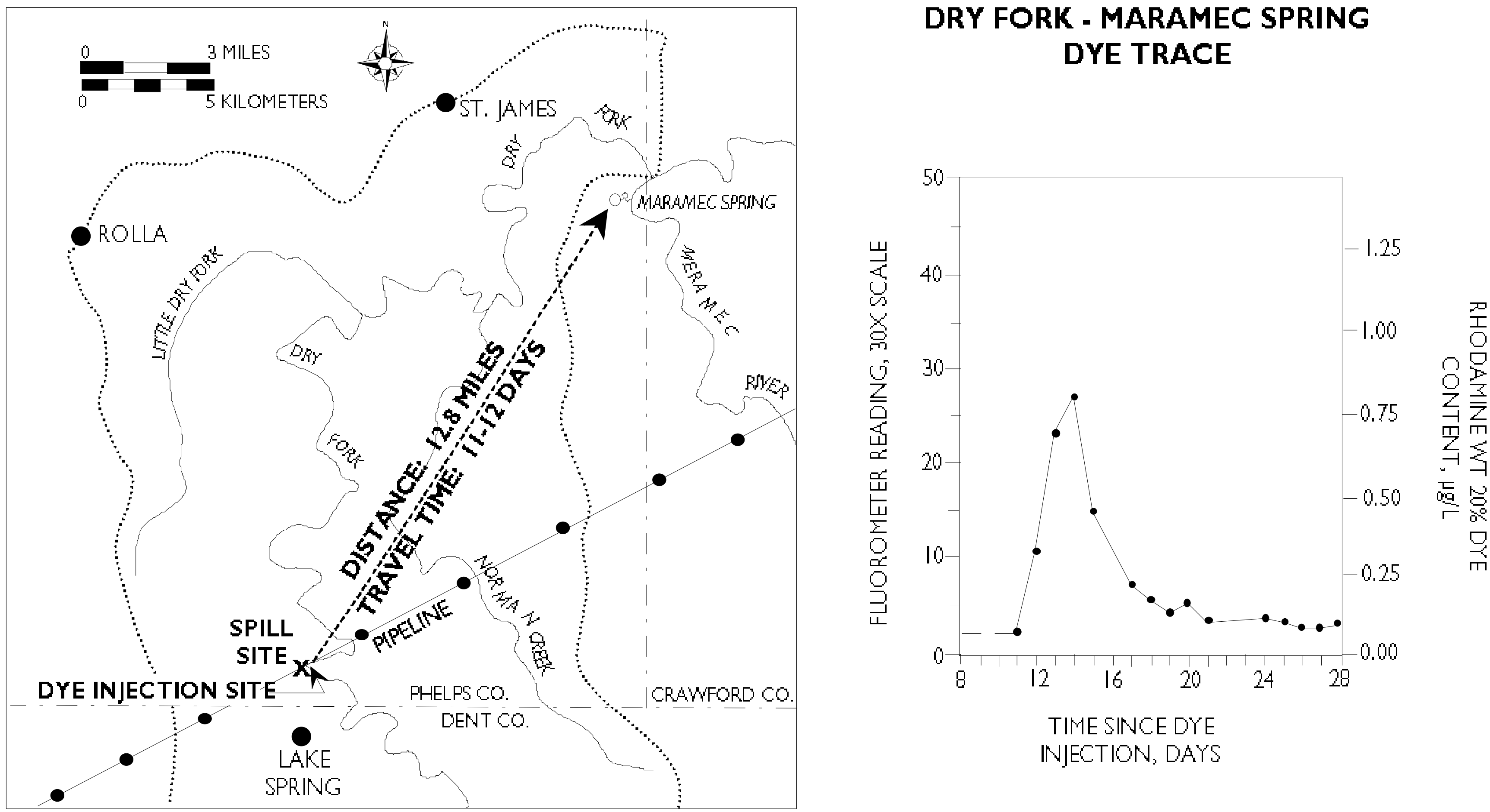


Figure 25. Results of the Dry Fork-Maramec Spring dye trace conducted in 1981 (from Vandike, 1985).

THE RECHARGE AREA OF MARAMEC SPRING

The dye traces show that the recharge area for Maramec Spring contains approximately 310 mi^2, which includes Dry Fork watershed upstream from Phelps County Route F, all of Norman Creek watershed, and all of Asher Hollow. Figure 26 shows the recharge area of Maramec Spring. The amount of the recharge area in Norman Creek watershed is about 52 mi^2. Asher Creek watershed contains about 12 mi^2 of recharge area. The remaining 246 mi^2 is within Dry Fork watershed.

Those familiar with the flow characteristics of Dry Fork, Norman Creek, and Maramec Spring know that the discharge of Maramec Spring is generally much greater than the dry-weather flows normally carried by these creeks and subsequently lost underground. Consider the seepage runs that have been conducted in this area. The 1969 seepage run conducted by the U.S.G.S. showed a measured loss of only about 4 ft^3/sec in Dry Fork and Norman Creek watersheds. At the time, the discharge of Maramec Spring was about 79 ft^3/sec, so at that time the volume of water being lost underground in the recharge area from surface flow amounted to only about 5 percent of the discharge at Maramec Spring. The 1982 seepage run, though conducted in wetter weather, showed a similar pattern. Water lost at losing zones of Dry Fork and Norman Creek totaled 20.1 ft^3/sec, or about 5 percent of the 393 ft^3/sec discharge occurring at Maramec Spring at the time.

The volume of water lost much of the time from Dry Fork, Norman Creek, and other streams in the recharge area supplies but a fraction of Maramec Spring's flow. Most of the recharge occurs during relatively brief periods following heavy rainfall when all of the losing streams, large and small, are losing flow into the subsurface, filling large and small openings that all interconnect with the conduits that transport water to the spring. In the uplands, water moves downward through saturated soils into smaller openings to begin the slow but sure trip to Maramec Spring. Losing streams such as Norman Creek and Asher Hollow will not carry flow throughout their length until water table elevation has raised to above streambed elevation, or unless the volume of water entering the streams is greater than the loss rate through the bed materials.

An inch of recharge within Maramec Spring's recharge area will provide about 5.4 billion gallons of water to Maramec Spring, enough to supply it for 54 days during average flow conditions. The size of recharge area necessary to supply water to a particular spring can be calculated from the equation:

$$A = 13.584\ Q / R$$

where: A = *Recharge area size (square miles)*
Q = *Average discharge of spring* (ft^3*/sec)*
R = *Recharge rate (inches of water per year)*

The above equation is simply a mass balance which states that the volume of discharge must equal the volume of recharge. In the Maramec Spring area, long-term runoff information for major rivers shows that a maximum average of about 12

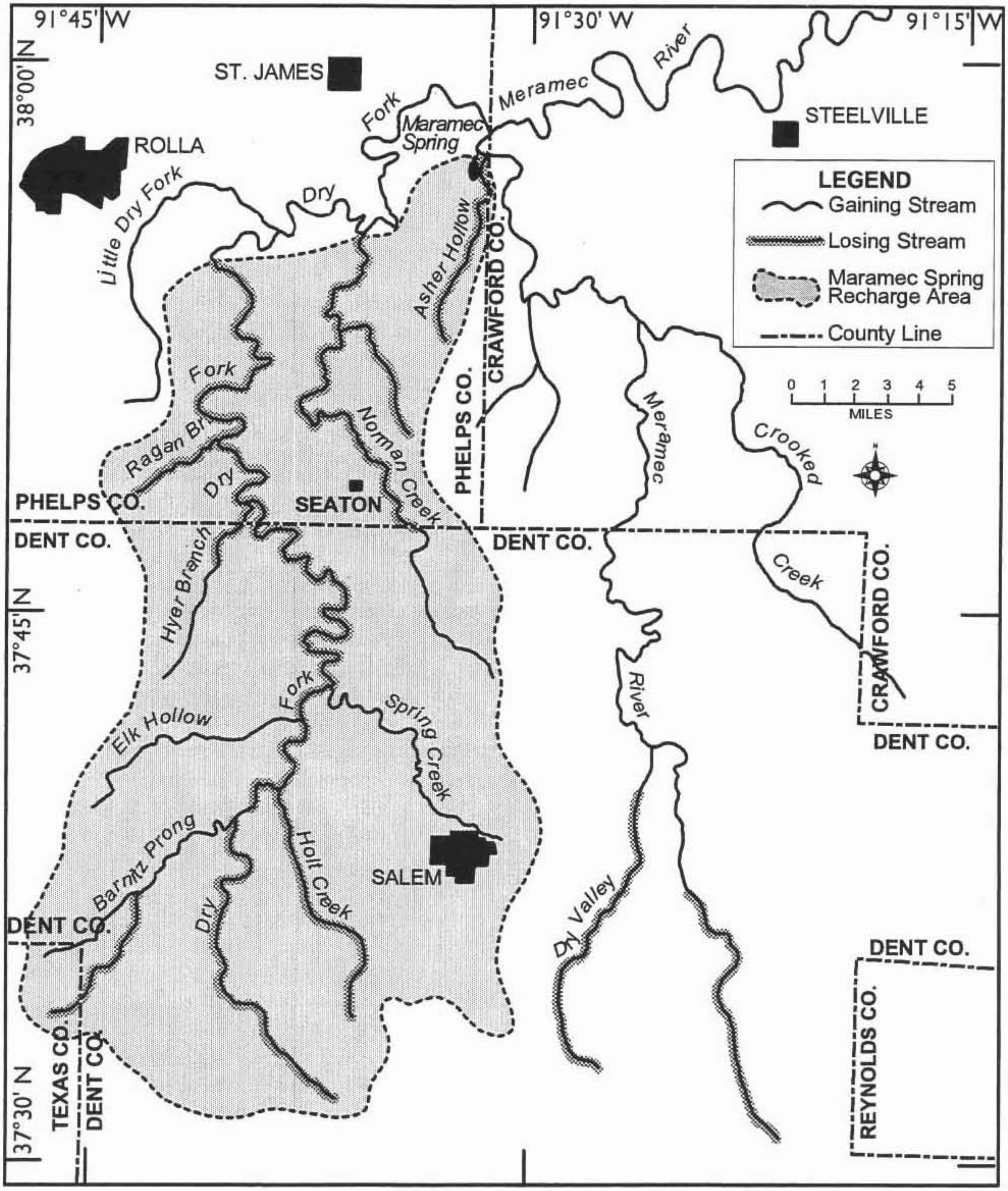


Figure 26. The recharge area of Maramec Spring.

inches of runoff is potentially available for groundwater recharge. If a recharge rate of 12 inches is used in the above equation, Maramec Spring could potentially be supplied by an area containing about 175 square miles. However, for this to occur, there could be no surface-water outflow from the recharge area; all of the water available after losses to evapotranspiration occurred would have to be channeled underground to provide recharge to Maramec Spring. This can occur in sinkhole plains, but in losing-stream settings such as Dry Fork, there is normally at least some surface-water outflow from the losing reaches after heavy rainfall.

Assuming a recharge area of 310 mi^2 and an average spring discharge of 155 ft^3/sec, the calculated average recharge rate for Maramec Spring's recharge area is about 6.8 inches. However, it is very unlikely that the recharge rate is a uniform amount throughout the recharge area. Surface-water runoff characteristics of Dry Fork, Norman Creek, and Asher Hollow provide some indications of the amount of recharge supplied by each.

Continuous discharge data are not available for Dry Fork, Norman Creek, or Asher Hollow. Skelton (1976) calculated the magnitude and frequency of low flows for numerous streams and springs in Missouri. Dry Fork at Missouri Highway 68, Maramec Spring, and the Meramec River at Cook Station, Missouri Highway 8, and Steelville were among them. Low-flow statistics for Maramec Spring and the Meramec River near Steelville are based on continuous data; statistics for the other sites are based on numerous instantaneous discharge measurements taken during dry periods a number of years.

Except for the area upstream of Missouri Highway 32 in Dent County, the Meramec River is a gaining stream. The 7-day Q_2 value for the Meramec River at Cook Station, with a drainage area of 199 mi^2, is 8.2 ft^3/sec. In other words, the average minimum flow for 7 consecutive days with a recurrence interval of 2 years is 8.2 ft^3/sec. The 7-day Q_2 of the Meramec River at Highway 8, which drains an area of about 326 mi^2, is calculated to be 22 ft^3/sec, and that for the Meramec River near Steelville is 120 ft^3/sec. Dry Fork at Missouri Highway 68, which drains an area of about 365 mi^2, is calculated to have a 7-day Q_2 flow value of only 1.2 ft^3/sec. The large increase in 7-day Q_2 values between the Meramec River at Missouri Highway 8 and at Steelville is, of course, the addition of flow from Maramec Spring, whose 7-day Q_2 is 70 ft^3/sec. The relatively small value for Dry Fork is also due to Maramec Spring, because of the subsurface transfer of water from Dry Fork watershed to Maramec Spring.

Other than occasional discharge measurements, surface-water runoff data are not available for any of the losing-stream watersheds providing recharge to Maramec Spring. This makes it impossible to accurately estimate the runoff rates for Dry Fork , Norman Creek, or Asher Hollow. All three of these streams have some surface-water discharge through their losing reaches during very wet weather, but observations made during both dry and wet weather indicate that Norman Creek and Asher Hollow carry flow through their losing reaches much less often than Dry Fork, and for far shorter periods of time. Average runoff rates can be estimated from long-term discharge information available for the Meramec River near Steelville. Upstream from the U.S.G.S. gaging station, which is at a railroad bridge about 400 ft upstream from the Missouri Highway 19 bridge, the Meramec River drains an area of 781 mi^2, and has an average annual runoff rate of about 10.4 inches (Hauck and others, 1996). Even though this gaging station is several miles downstream from Maramec Spring, almost 93 percent, or 726 mi^2 of its

drainage area, consists of drainage from Dry Fork and the Meramec River upstream from Dry Fork.

Most of the runoff in Norman Creek and Asher Hollow enters the subsurface and resurfaces at Maramec Spring. Assuming an average annual runoff rate of 10.4 inches in these watersheds, it is likely that at least 9 inches of that is carried underground to provide recharge to Maramec Spring. The yearly discharge of Maramec Spring averages about 36.59 billion gallons of water. Based on a recharge rate of 9 inches, recharge from Norman Creek supplies about 22.2 percent of this, or about 8.12 billion gallons. Asher Hollow, whose flow characteristics are much like those of Norman Creek, supplies about 5.1 percent of the recharge for Maramec Spring, or about 1.88 billion gallons. The remaining recharge is supplied from Dry Fork watershed upstream from Phelps County Route F. Dry Fork is known to have surface flow through the losing reaches more often and for longer periods than Norman Creek, and the watershed likely has a lower groundwater recharge rate. An average annual recharge rate of 6.22 inches occurring in Dry Fork upstream from Route F would supply the needed volume of recharge, 26.59 billion gallons or about 72.2 percent of the total recharge received by Maramec Spring.

Although long-term discharge information from the gaging station on the Meramec River near Steelville indicates that total runoff in the upper Meramec River basin, surface and subsurface, is about 10.4 inches per year, this value may be misleading. Regional runoff maps developed by Skelton (1971), and records from other long-term surface-water gaging stations in the central Ozarks, show that regional runoff varies from about 11.5 inches per year in the northern part of the study area to about 13 inches in the southern part. This suggests that a more representative average annual runoff value for this area is about 12 inches.

If, as regional data suggests, the average annual runoff rate is 12 inches rather than 10.5 inches, the above percentages of recharge supplied by each of the watersheds would change slightly. If groundwater recharge was 11 inches per year rather than 9 inches as estimated above, Norman Creek would supply about 27 percent of Maramec Spring’s recharge, or about 9.92 billion gallons. Asher Hollow would supply about 6.3 percent of the recharge, or about 2.29 billion gallons per year. Under this scenario, Dry Fork upstream of Phelps County Route F would supply less recharge, about 66.7 percent of the recharge or about 24.38 billion gallons per year. To do so, an average recharge rate of about 5.7 inches per year would be required. The discrepancy between the regional runoff values and those measured at the Steelville gaging station may be due to interbasin transfer of groundwater from the upper Meramec into adjacent watersheds, such as the Current River. There are several pieces of indirect evidence that support this theory, including runoff rates from streams, and dye tracing information.

The average annual runoff of the Meramec River upstream from near Steelville appears to be about 2 inches less than expected for this area. For about 16 years, the U.S.G.S. operated a second gaging station on the upper Meramec River at the village of Cook Station, which is several miles upstream from Maramec Spring. The Meramec River upstream from Cook Station drains an area of 199 mi^2. Between October 1965 and November 1981, discharge of the river here averaged 110 ft^3/sec. Average annual basin runoff was only 7.51 inches, a very low value for this part of the Ozarks. Most of the Meramec River basin upstream from Missouri Highway 8 near Maramec Spring is characterized by gaining streams. The most notable exception to this is the Meramec River drainage upstream of Missouri Highway 32 east of Salem, and nearby Dry Valley, a Meramec River tributary. The area drained by losing

streams in this area is approximately 80 mi². There are several small springs along the Meramec River and its tributaries between Missouri Highway 32 and Maramec Spring, but none that could account for the volume of water lost underground in the upper part of the basin. Also, there is no reason to believe that the Meramec River basin upstream from Missouri Highway 32 provides recharge to Maramec Spring. The most logical explanation is that the water is diverted in the subsurface into an adjacent watershed, most likely to the south into the Current River basin.

The same may be occurring in the upper watershed of Dry Fork. Dye tracing was successful in demonstrating that water lost into the subsurface in the several mile-long losing reach of Dry Fork upstream from Phelps County Route F provides recharge to Maramec Spring. Obviously, surface-water runoff from any point in the watershed upstream from this losing reach also has the potential for providing recharge to Maramec Spring simply by reaching the losing stretch as surface flow, and then traveling underground the remaining distance to Maramec Spring. Dye tracing, however, has not demonstrated that water lost into the subsurface through sinkholes and losing streams in the upper part of Dry Fork watershed provides recharge to Maramec Spring. Two traces attempted during this study in the upper part of Dry Fork watershed were inconclusive. The dyes were not detected at any of the springs monitored. Two other dye traces attempted in this area in 1986 and 1987 ended with similar results. The injection sites of these four unsuccessful of dye trace attempts are shown in figure 27.

On October 1, 1986, following heavy, prolonged rainfall, 5 pounds of fluorescein dye was introduced into runoff entering a large sinkhole about 1.5 miles southwest of the village of Darien in the SE 1/4 Sec. 32, T. 33 N., R. 6 W. The sinkhole is one of several large, deep sinkholes developed along the surface-water drainage divided between Dry Fork and the Current River at the northern end of Inman Hollow. The dye was injected about 1/2 mile south of the southern end of Dry Fork watershed.

Numerous springs including Montauk, Welch, Round, and Shaffer springs in the Current River basin; Piney, Finn, and Lane springs in the Little Piney Creek basin, Relfe and Stone Mill springs in the Big Piney basin, and Maramec Spring, as well as numerous gaining-stream reaches in all of the above watersheds, were monitored for dye for several months. Dye was not recovered at any of the locations monitored.

Another trace was attempted from the channel of Dry Fork in the southern part of Sec. 6, T. 34 N., R. 6 W., about three miles upstream from Missouri Highway 72. On October 16, 1987, 15 pounds of fluorescein dye was injected into a series of pools in Dry Fork. There was no discharge from the pools downstream, and the creek remained dry for the next several miles downstream. Once again, numerous springs and gaining streams in the area, including those mentioned above, were monitored for dye. Dye from this trace was not recovered at any of the sites monitored.

There are numerous reasons why a dye trace can end with inconclusive results. These include using an insufficient quantity of dye, not monitoring the site where the dye reappeared, monitoring for an insufficient length of time, selecting a poor dye-injection site, inadequate subsurface inflow at the injection site, overly dry conditions, and a host of others that can adversely affect the outcome of a dye trace. Which of these factors, if any, were responsible for the failures of 4 dye trace attempts in the upper Dry Fork area is not known. Based on numerous other traces in the area, the quantities of dye that were used do not appear unreasonably small. All of the injection sites were known to provide groundwater recharge. All of the springs that seemed likely to receive the dye, plus several that were not, were monitored.

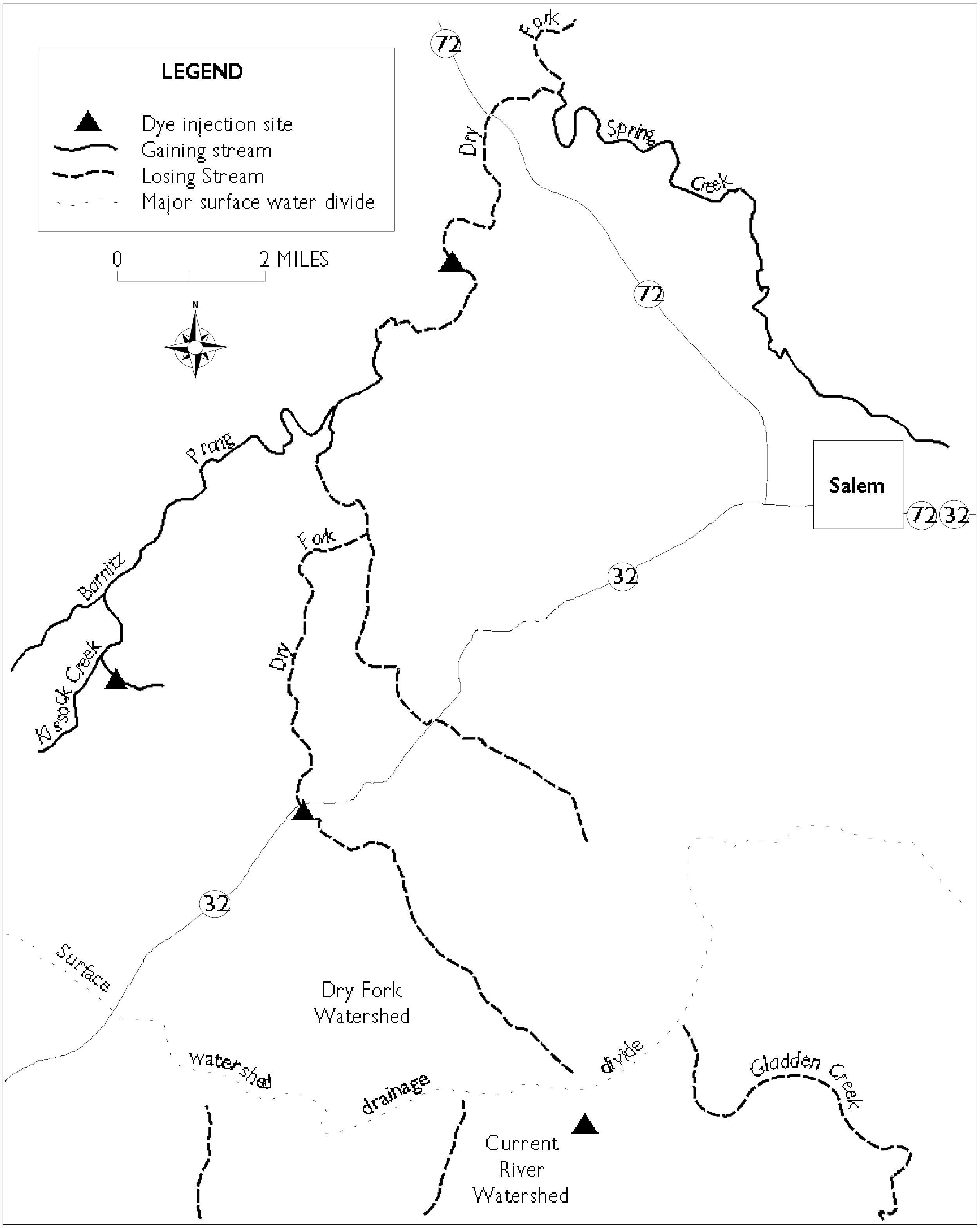


Figure 27. Dye injection locations of unsuccessful dye trace attempts in upper Dry Fork basin.

None of the traces were attempted in extremely dry weather.

One factor that may have contributed to the dye traces problems is the deep bedrock weathering in area. Residuum thickness in the area can exceed 100 ft, and the dyes used for groundwater tracing are much better suited for use in clean bedrock conduits than in areas where there is considerable clay and silt in contact with groundwater. Both fluorescein and Rhodamine WT are adsorbed by clays to some degree, and if the quantity of dye being used was marginal, such conditions could have prevented adequate dye from being recovered at the receiving spring.

Since so many traces have ended in failure in a relatively small geographic area, it is more likely that groundwater in the upper part of Dry Fork watershed is recharging a spring or springs that were not monitored during the studies. There are several springs in the upper Current River that are accessible from the river but difficult to reach by road, and at best are inconvenient to monitor. Cave Spring and the Pulltite Spring complex are among these.

Aley (1982) reports a dye trace that was attempted from an upper Dry Fork tributary in the NW 1/4 Sec. 6, T. 33 N., R. 6 W. that was possibly recovered at Welch Spring. Visual techniques were used to analyze for the dye. Although 10 pounds of fluorescein was injected, so low was the visual fluorescence from samples collected at Welch Spring that Aley termed the trace possible. No dye was detected from this trace at Montauk Spring. Maramec Spring was not monitored.

Date of Collection and Data Source	Rate of Flow (ft^3/sec)	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3-N)	Total Phosphorus (P)	Dissolved solids (Residue at 180°C)	Hardness as $CaCO_3$: Calcium-Magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific Conductance (microsiemens)
6/25[1]	111	—	6.2	.87	30	18	3.3		163	8	2.7	2.4	—	.38	—	153	149	1	—
8/34[1]	86.9	58	—	.30	37	21	5.0		218	1	5.1	2.7	—	.56	—	259	179	—	—
11/53[1]	—	58	5.2	.10	39	23	4.1		225	0	2.9	4.0	.1	.51	—	194	190	6	—
6/64[1]	78.3	53	1.4	.12	32	18	.2		174	0	5.2	3.0	.0	.47	—	166	154	11	—
8/64[1]	67.4	58	14.0	.07	37	21	3.4	.9	209	0	4.4	4.0	.1	.80	.03	191	179	8	346
11/65[1]	63.8	57	9.4	.00	33	18	2.7	.8	187	0	5.2	2.6	.0	.76	—	167	157	4	306
2/66[1]	75.6	56	8.8	.03	31	17	2.4	.7	171	0	5.6	2.5	.1	.51	—	154	148	8	280
5/66[1]	290	56	9.9	.04	23	10	1.6	1.2	109	0	6.2	1.1	.1	.62	—	116	97	8	194
11/23/81[2]	150	59	—	.11	26	13	2.7	1.8	150	0	2.0	2.0	—	3.6*	—	181	119	—	270
11/24/81[2]	145	—	—	.11	27	14	2.6	2.0	148	0	2.0	3.0	—	5.1*	—	179	121	4	—
11/25/81[2]	145	58	—	.11	24	13	2.8	2.4	150	0	2.0	3.0	—	5.4*	—	178	114	—	295
11/26/81[2]	150	59	—	.10	25	13	2.9	2.3	148	0	2.0	3.0	—	4.9*	—	232	116	—	305
11/27/81[2]	145	59	—	.08	26	14	2.9	2.3	155	0	2.0	3.5	—	5.4*	—	186	123	—	305
11/28/81[2]	145	59	—	.13	26	13	2.8	2.1	161	0	2.0	3.0	—	5.6*	—	183	119	—	310
11/29/81[2]	145	58.5	—	.18	25	14	3.0	2.2	162	0	2.0	3.0	—	5.6*	—	187	120	—	320
11/30/81[2]	154	58.5	—	.07	24	14	3.0	2.2	162	0	2.0	2.5	—	5.7*	—	190	118	—	320
12/3/81[2]	335	58.5	—	.07	27	14	3.1	1.49	170	0	3.0	3.0	—	2.8*	—	170	125	—	295
11/17/93[3]	1100	56.3	—	—	—	—	—	—	123	0	—	—	—	.56	.04	—	—	—	167
1/20/94[3]	135	54.5	—	.005	30	17	2.9	1.3	215	0	5.8	4.4	<.1	.83	.02	156	140	—	275
3/8/94[3]	255	53.6	—	—	—	—	—	—	114	0	—	—	—	.70	.03	—	—	—	234
4/26/94[3]	800	54.5	—	—	—	—	—	—	101	0	—	—	—	.66	<.02	—	—	—	193
6/23/94[3]	135	54.5	—	.01	27	15	2.6	1.4	156	0	5.2	3.9	<.1	.72	.03	146	130	—	250
8/29/94[3]	80	57.2	—	—	—	—	—	—	178	0	—	—	—	.77	.02	—	—	—	314
11/3/94[3]	130	57.2	—	—	—	—	—	—	195	0	—	—	—	.80	.04	—	—	—	337
1/13/95[3]	285	55.4	—	.005	33	19	3.7	1.2	177	0	5.9	5.9	<.1	.77	.02	166	160	—	311
3/22/95[3]	90	55.4	—	—	—	—	—	—	118	0	—	—	—	.72	.05	—	—	—	216
4/17/95[3]	216	55.4	—	—	—	—	—	—	128	0	—	—	—	.58	<.02	—	—	—	223
6/7/95[3]	254	56.3	—	.025	21	12	2.2	1.4	118	0	5.7	3.5	.1	.54	<.02	122	100	—	209
8/8/95[3]	140	58.1	—	—	—	—	—	—	161	0	—	—	—	.73	.02	—	—	—	292

Data Sources:
1 - Springs of Missouri (Vineyard and Feder, 1982)
2 - Water Quality Files, DGLS
3 - U.S.G.S. Water Resources Data Reports, water years 1994 and 1995

* Nitrate concentration affected by fertilizer pipeline leak
— Not determined

Table 8. Water-quality data for Maramec Spring from various sources.

WATER QUALITY

Water quality at Maramec Spring is generally very good. The moderately mineralized calcium-magnesium-bicarbonate type water reflects the composition of the dolomitic bedrock, and most of the constituents in the water are dissolved from the rock. Calcium, magnesium, and bicarbonate are the ions generally present in the highest concentrations. Calcium, magnesium, and bicarbonate analyses were made of samples collected each four hours at Maramec Spring for a 13 month period beginning November 1985 as part of a cooperative study between the University of California-Santa Cruz, and the Missouri Division of Geology and Land Survey. These constituents varied depending on recharge, being highest during dry weather when the spring was discharging water that had been in contact with rock in the aquifer for a relatively long time. During the 13 month period, calcium varied from about 15 mg/L to 37 mg/L, magnesium varied from about 7 mg/L to 20 mg/L, and bicarbonate varied from 80 mg/L to about 200 mg/L.

Water-quality data are available from Maramec Spring from as early as 1925. Analyses for major ions were made in 1925, 1934, 1953, 1964, 1965, 1966, 1981, 1992, 1993, 1994, and 1995 (table 8). Analyses made prior to 1981 are also shown in *Springs of Missouri* (Vineyard and Feder, 1982).

Ions such as potassium, sodium, sulfate, chloride, phosphate, and nitrate are all present in low concentrations. Some of these can be present as a result of weathering of the bedrock, but more often are related to waste disposal, agricultural fertilizers, or other activities in the recharge area. Chloride, sulfate, potassium, and sodium concentrations are generally very low, less than 5 mg/L each, and unlike calcium, magnesium, and bicarbonate, they do not appear to vary greatly in response to recharge.

Nitrate and phosphate are both present in very low concentrations in natural waters, but elevated levels are generally due to human or animal waste, or fertilizer. Total nitrogen is almost always less than 1 mg/L at Maramec Spring, and is generally less than 0.5 mg/L. Since the water normally contains more than 7 mg/L dissolved oxygen, the nitrogen is mostly in the form of nitrate. Nitrite and ammonia are normally very low or below detection limits. Total phosphorus is generally below .05 mg/L, and orthophosphorus is generally less than 0.02 mg/L. Iron and manganese, the most common metals found in groundwater in the Ozarks, are present in low concentrations at Maramec Spring. Iron is the highest of the two, generally less than 0.3 mg/L, and manganese is generally less than 0.01 mg/L. Total dissolved solids generally are between 120 mg/L and 300 mg/L.

The lack of large towns within the recharge area helps in terms of water quality. Salem is the largest town in Dry Fork basin, and treated wastewater from there is released into Spring Creek, a Dry Fork tributary. Spring Creek, however, is a gaining stream, and natural biologic processes remove much of the nutrient load

from the water before it enters a losing-stream section of Dry Fork and potentially becomes groundwater recharge. Septic tanks, livestock lagoons, livestock, and fertilizer are present in the recharge area, and add to the nutrient load.

Since 1993, Maramec Spring has been part of the U.S.G.S. Ambient Water-Quality Monitoring Network. The U.S.G.S. collects water-quality samples at the spring approximately every two months. The samples are analyzed for many of the constituents listed above, but also for bacteria counts and determinations for various metals. Two samples collected in 1994 were analyzed for various pesticides. The metals include iron and manganese, discussed previously, and aluminum, cadmium, copper, lead, mercury, and zinc. Most of these metals are not present in quantities above analytical detection limits at Maramec Spring (Reed and others, 1995). In 1994, samples were collected for metals analyses on January 20 and June 23. Both samples showed total aluminum to be 40 micrograms per liter (µg/L). One microgram per liter is essentially equal to one part per billion. The January sample contained 1 µg/L total lead, and both samples contained 0.1 µg/L total mercury. Total zinc was 6 µg/L in the January sample and 4 µg/L in the June sample.

In 1995, samples for metal analyses were collected on January 13 and June 7. Copper was detected in one sample at a concentration of 1 µg/L. Total aluminum in the January sample was 50 µg/L, and in the June sample was 110 µg/L. No dissolved lead was detected, but total lead in the June sample was 2 µg/L, and total mercury in the June sample was 0.2 µg/L (Hauck and others, 1996).

Samples collected April 26 and June 23, 1994, were analyzed for 46 pesticides. Only a few of the pesticides were present above analytical detection limits, and those that were detected were present in minute quantities. The April sample contained 0.02 µg/L Cyanazine, 0.01 µg/L Atrazine, and 0.01 µg/L Diazinon. The June sample contained 0.003 Deethylatrazine, 0.03 µg/L Atrazine, and 0.01 µg/LTebthiuron.

Bacteria samples collected between November 17, 1993, and August 8, 1995, show that fecal coliform and fecal streptococci are typically present in the spring. Fecal coliform varied from 21 to 160 colonies per 100 milliliters (cols./100 ml). Fecal streptococci was present in similar numbers, ranging from 23 to 180 cols./100 ml. Both of these types of organisms are indications human or other animal wastes. Their presence is significant for at least three reasons. First, it shows that wastes in the recharge area affect water quality at Maramec Spring. Second, it shows that water moving through karst drainage systems does not remain underground long enough for bacteria to die off. Third, it shows that the water moving through the spring system is not effectively filtered by the earth materials, a common misconception held by many people. The types of bacteria present in water discharging from Maramec Spring are likely present in most springs in the Ozarks. Thus, without disinfection, springs should not be considered safe sources of drinking water.

Except possibly for a very small increase in nitrate, less than 0.2 mg/L, water quality at Maramec Spring does not appear to have changed appreciably in the past 50 years.

HISTORICAL WATER-QUALITY PROBLEMS AT MARAMEC SPRING

Water quality has not always been so good at Maramec Spring. A liquid fertilizer pipeline leak caused severe water-quality problems for a several week period in 1981. An estimated 24,000 gallons of ammonium nitrate and urea fertilizer with a nitrogen content of 32 percent leaked from a pipeline at the west edge of Dry Fork floodplain. The spill took place on the Ken Lennox farm about one mile north of the Phelps-Dent County line, 12.8 miles southwest of Maramec Spring (figure 28). For a short distance downstream from the leak site, Dry Fork normally consists of a series of pools recharged by several small springs. Less than a mile downstream, though, flow disappears into the subsurface, and there is normally little or no flow in Dry Fork for the next several miles downstream (Vandike, 1982).

The pipeline leak was discovered on November 15, 1981, but it likely had been leaking at least several days before the fertilizer surfaced. Spill estimates supplied by the pipeline company indicated that a relatively small amount of fertilizer, about 1,344 gallons, leaked from the line. However, on November 22, seven days after the leak was reported, water-quality began degrading at Maramec Spring. A sharp decline in dissolved oxygen was the first indication that the fertilizer was affecting the spring. Ammonium nitrate and urea both have high chemical oxygen demands. In the presence of ample oxygen, ammonium nitrate (NH_4NO_3) will convert first to nitrite (NO_2), and finally to nitrate (NO_3). Dissolved oxygen at Maramec Spring normally ranges from 7 mg/L to more than 10 mg/L. In the days following the pipeline leak, the dissolved oxygen level of Maramec Spring declined to less than 0.2 mg/L, far below the level necessary to sustain most aquatic life. Several hundred pounds of Rainbow Trout and an estimated 37,000 sculpins died. Thousands of small trout in rearing pools next to the spring branch were kept alive until they could be evacuated to other trout springs by using large pumps spraying water from the spring through the air to increase its oxygen content.

Figure 29 shows precipitation along with spring discharge, dissolved oxygen, nitrite+nitrate, and ammonia at Maramec Spring during this period. Dissolved oxygen remained below 1 mg/L for eight days. When dissolved oxygen was lowest, it was not sufficient to convert ammonia to nitrite and nitrate, so ammonia concentrations began increasing, reaching a peak of about 2.4 mg/L. About two weeks after water-quality problems began, conditions began to improve and did so for several days. Dissolved oxygen recovered to nearly 7 mg/L, and nitrogen content had decreased to less than 2 mg/L when a second drop in dissolved oxygen began about December 12. This second event paled in comparison to the first, with dissolved oxygen declining only to about 5 mg/L and nitrogen increasing to less than 3 mg/L,

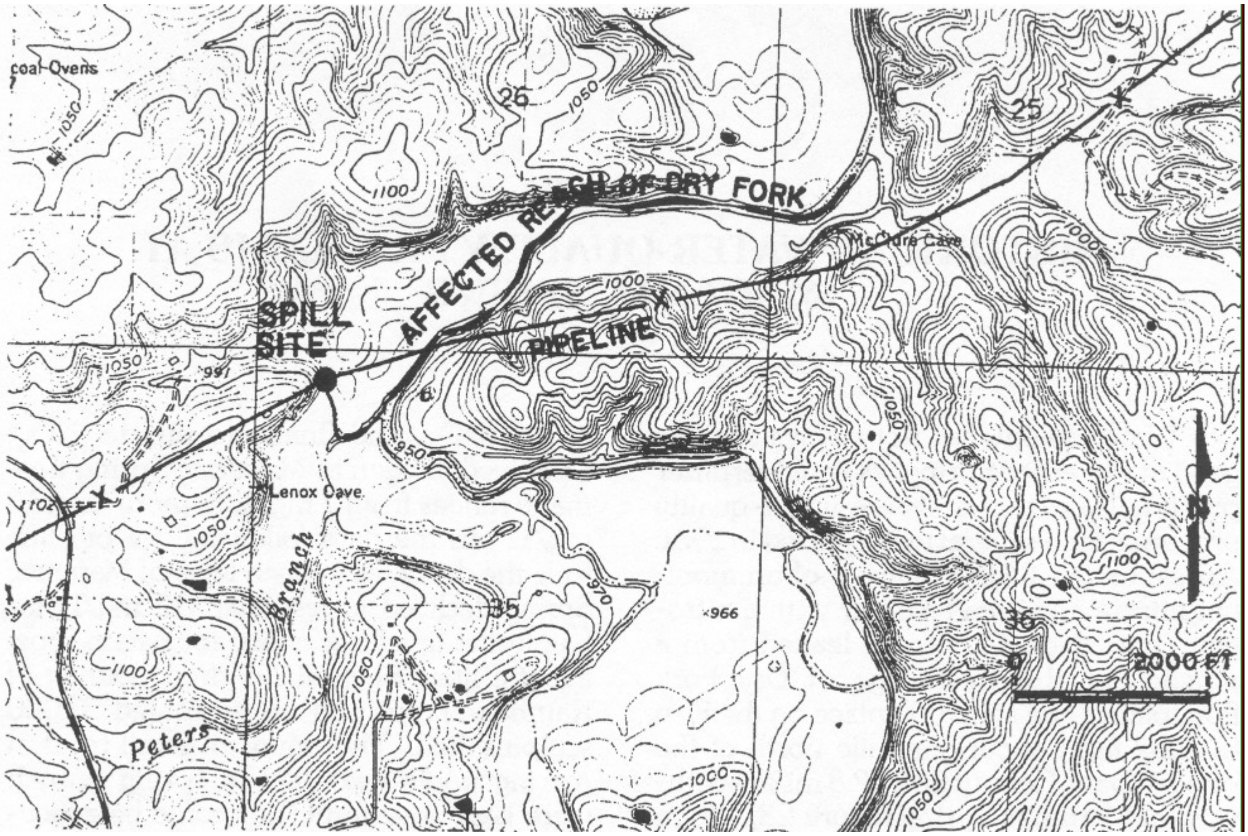


Figure 28. (Top) Topographic map of the 1981 fertilizer pipeline leak. Topography from the Lecoma 7 1/2' quadrangle. (Bottom) Areal Photo of the spill site, looking southwest. Photo by Jim Vandike.

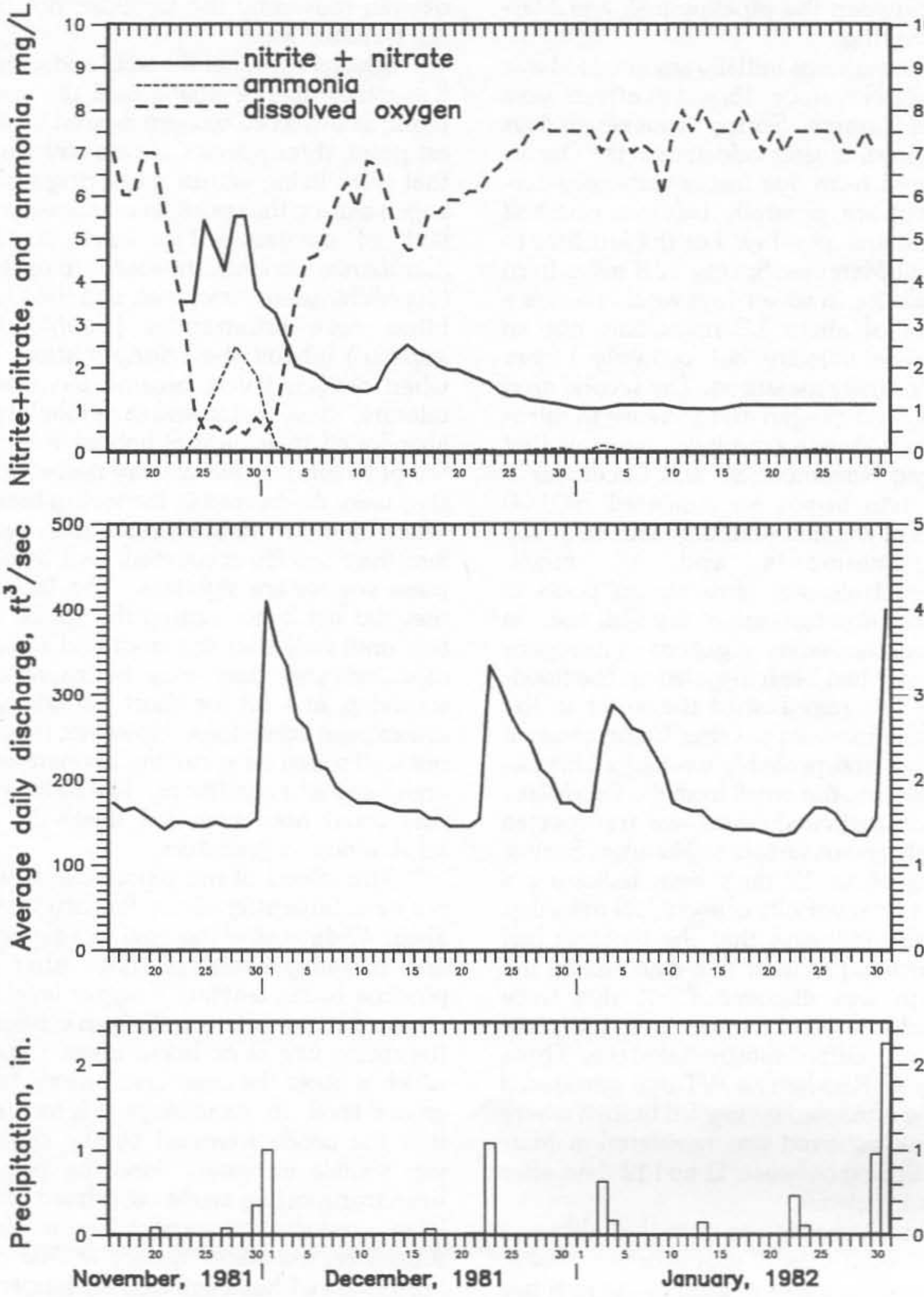


Figure 29. Discharge and water quality at Maramec Spring, and precipitation at Rolla-UMR, November 1981-January 1982.

but it helped to determine the actual travel time between the pipeline leak and Maramec Spring.

The leak was initially assumed to have began on November 15, and its effects were seen at Maramec Spring about seven days later. Groundwater velocities in the Ozarks measured from dye traces vary considerably, but are generally between one-half and one mile per day. For the fertilizer to arrive at Maramec Spring, 12.8 miles from the spill site, in seven days would require a velocity of about 1.8 miles/day, not an impossible velocity but certainly higher than normally measured. The second drop in dissolved oxygen and increase in nitrogen probably is the result of heavy rain that occurred November 30 and December 1. When rain began, an estimated 750,000 gallons of water containing as much as 130 mg/L ammonia and 44 mg/L nitrite+nitrate still remained in pools in Dry Fork downstream of the spill site. In addition, thousands of gallons of nitrogen-rich water had been irrigated on the floodplain. The rain flushed the water in the pools downstream to other losing zones of Dry Fork and probably washed additional fertilizer into the creek from the floodplain. The contaminated water was transported through the subsurface to Maramec Spring, arriving about 12 days later, indicating a groundwater velocity of about 1.07 mile/day. This also indicates that the pipeline had been leaking at least five days before the problem was discovered. A dye trace conducted several months after the pipeline leak occurred substantiated this. Three gallons of Rhodamine WT dye introduced into the unnamed spring-fed branch where the leak occurred was recovered at Maramec Spring between 11 and 12 days after it was injected.

It is interesting to note that although severe water-quality problems occurred at Maramec Spring as a result of the fertilizer pipeline leak, the total nitrogen content of the water peaked at about 6.2 mg/L, well below the 10 mg/L drinking water limit. The fish kill resulted from low dissolved oxygen caused by the fertilizer, not from the fertilizer itself.

Several days after the trout and sculpins had either died or abandoned the spring basin, as dissolved oxygen neared its lowest point, three species of rare cave fauna that were living within the spring system began exiting the spring in response to the lack of oxygen. The cave crayfish (*Cambarus hubrichti*), the southern cavefish (*Typhlichthys subterraneus*), and the Ozark blind cave salamander (*Typhlotriton speleaus*) inhabit the spring system, and when oxygen levels became too low to tolerate, these spring and cave inhabitants abandoned their natural habitat in an attempt to survive. Many were netted when they were discovered in the spring branch. When placed in aerated water in an aquarium they quickly recovered. All three of these species are sightless. The fact that they did not begin exiting the spring system until well after the trout and sculpins died indicates they may be capable of surviving, at least for short periods, very low oxygen conditions. However, they are not well suited for surviving in open water under daylight conditions. The individuals that could not be netted likely did not survive due to predators.

The effects of the pipeline leak were not detectable after about January 1, 1982, about 47 days after the spill was reported, and probably about 52 days after the pipeline began leaking. Oxygen level had returned to normal, and nitrogen content of the spring was at or below about 1 mg/L, which is about the maximum historic background level. In many ways, it is fortunate that the product carried by the pipeline was soluble in water. Had the pipeline been transporting crude oil, refined petroleum products, or some other insoluble substance, the water quality at Maramec Spring would have suffered far longer.

The pipeline which devastated aquatic life at Maramec Spring in 1981 no longer presents any environmental risk. Today, it

is used as a conduit for fiber optics communications cables, and carries no potential groundwater contaminants.

Data collected from private water supply wells in the area between the pipeline leak and Maramec Spring, and lower Dry Fork watershed, show that the contaminants followed a well-defined flow path, and did not cause widespread contamination in the shallow aquifer. In the days and weeks following the pipeline leak, health officials collected samples from 381 private wells in the area. About 50 percent of the wells contained less than 1 mg/L nitrate (as nitrogen); approximately 96 percent contained less than 10 mg/L, which is the recommended maximum nitrate content for drinking water.

Seventeen wells contained more than 10 mg/L nitrate. Sixteen of them were sampled for more complete analyses. The high-nitrate well which was not sampled was used for livestock watering, and it could not be sampled except from an open stock tank that was exposed to the elements. Elevated chloride and sulfate concentrations in many of the wells indicated they were receiving contaminants from nutrient-rich sources other than the pipeline, such as septic systems, livestock feed lots and barnyards. Nitrate concentrations were monitored for a several month period at most of the wells. Although nitrate levels increased and decreased quickly at Maramec Spring following the pipeline leak, nitrate levels in the private wells remained nearly constant. Many of the wells were also found to contain bacteria. Fluorescent dyes were used to show that wastes from the septic systems were entering some of the wells. None of the wells could be shown to have been affected by the pipeline leak.

Water-soluble contaminants entering a karst drainage system through a sinkhole or losing stream can be expected to follow a well-defined flow path through discrete conduits. The contaminants will certainly affect water quality within the conduit, and at the receiving spring or springs, but probably will not affect a large area away from the conduit. The conduits serve as drains, water moves into them from the adjacent aquifer. After heavy rainfall when head pressure inside the conduit increases in response to recharge, water may move from the conduit into the adjacent aquifer. This outflow from the conduit into the aquifer probably lasts only a few hours or days, at which time flow reverses and water again moves from the aquifer into the conduit. Unless a well is located very close to a conduit, the chances of contaminants moving through the conduit affecting the well are probably slight.

HYDROLOGIC CHARACTERISTICS OF MARAMEC SPRING AND ITS RECHARGE AREA

The recharge, transport, and discharge characteristics of every spring differs. These differences are controlled by the geology of the recharge area, its size, the degree of interconnection of subsurface openings, the residence time of recharge, size and shape of the spring conduit, and a host of other factors. At ungaged springs where there is little water quality or dye tracing data, knowledge about the hydrologic characteristics are typically lacking. As more information becomes available, it becomes possible to explain and even predict the spring's response to precipitation.

The relationship between precipitation and spring recharge can easily be seen by comparing changes in flow at the spring with precipitation. The discharge of Maramec Spring will begin increasing within a few hours after heavy rainfall begins in the recharge area. However, the water emerging from the spring while the flow is increasing is water that was within the system when rainfall started. The recharge provided by the rainfall does not reach the spring for several days. Dye tracing in the Maramec Spring area shows groundwater velocities ranging from less than one-half mile per day to about one mile per day. The arrival of fresh recharge from a rainfall event at Maramec Spring is signaled not by the change in discharge, but by a change in water quality. Rainfall contains very little dissolved minerals. Upon striking the Earth, it begins dissolving materials, mostly from the dolomitic bedrock. However, it takes several weeks or months for this water to dissolve its full mineral load, and much of the water will pass through the spring system long before this occurs. The arrival of the recharge can be readily detected by collecting frequent water samples and analyzing them for calcium. Figure 30 shows the relationship between precipitation, discharge, and dissolved calcium at Maramec Spring between December 1985 and November 1986. Heavy rainfall results in an almost instantaneous increase in spring discharge as recharge entering the subsurface in the recharge area increases the pressure on water already in the spring system. A few days later, calcium content of the water begins decreasing as the fresh recharge arrives at the spring.

Maramec Spring has its highest discharge during wet weather when rainfall is frequent, the soils are saturated, and groundwater recharge rates are high. However, flow at the spring does not cease during dry weather. Even during extended droughts, Maramec Spring has an impressive discharge. But instead of relying on recharge from precipitation, the flow during droughts is derived from water in storage in the aquifer.

The volume of data collected at Maramec Spring and in its recharge area in 1994 and 1995 allow a much better understanding of how the spring responds to recharge. Hourly precipitation data are available for four precipitation stations within Dry Fork watershed, and daily precipitation data is available from two more, one a few miles south of Dry Fork watershed in the upper Current River basin. Hourly discharge and specific conductance

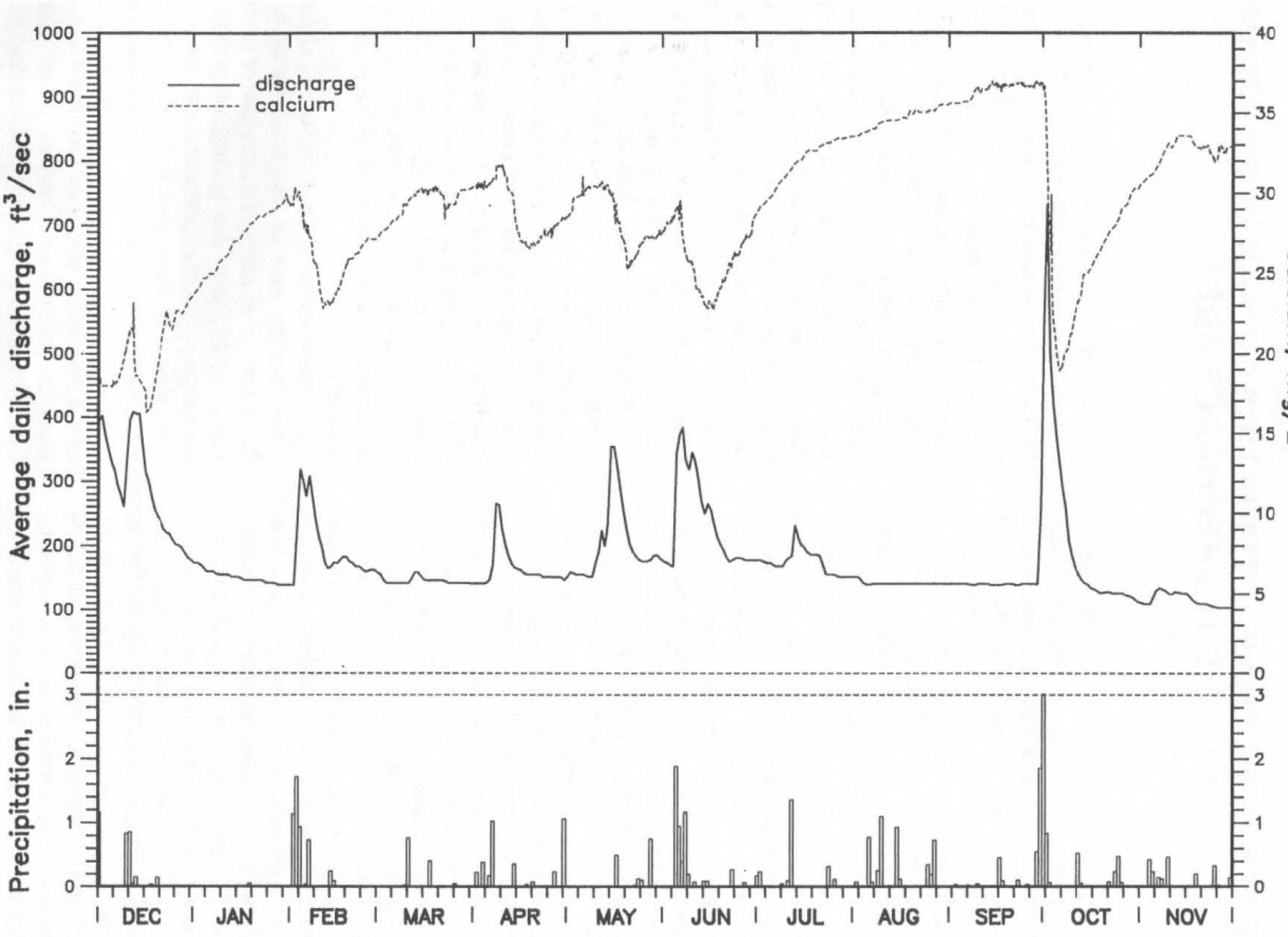


Figure 30. The effects of precipitation on discharge and calcium concentrations at Maramec Spring, December 1985 through November 1986.

data are available at Maramec Spring. Lacking, of course, is detailed flow information from key surface-water drainages such as Dry Fork and Norman Creek. This information would have been very helpful in describing the interrelationship between these losing streams and discharge at Maramec Spring, but even without it the available data is sufficient to show how the spring responds to recharge events.

Maramec Spring's response to precipitation depends greatly upon soil moisture at the time precipitation occurs. During the drier times of the year, generally from mid-July through the fall, Dry Fork watershed can receive fairly substantial rainfall with no corresponding change in discharge or water quality at Maramec Spring. An inch or more of precipitation occurring when the soil moisture is well below field capacity may not be sufficient to generate any appreciable surface-water runoff or groundwater recharge. The same inch of precipitation occurring during the wetter part of the year, generally from March through June, may cause a significant change in discharge at Maramec Spring.

The following analyses of storm events and the changes in water quality and discharge at Maramec Spring triggered by them will help illustrate how the spring responds to precipitation, and show the complexities of its drainage system.

Late in the evening of February 19, 1994, precipitation began falling in the Rolla area. Between 2100 hrs on February 19 and 0100 hrs February 20, 0.37 inches of rain fell. Precipitation at the southern end of Dry Fork watershed was higher; Salem reported 0.74 inches. Soil moisture was high at this time as a result of an abnormally wet summer and fall in 1993. Discharge at Maramec Spring began increasing slightly on February 20 between 0800 and 0900 hrs, about 11 hours after precipitation began at Rolla, increasing from 152 ft^3/sec to a high of 162 ft^3/sec on February 21 at noon (figure 31).

Precipitation resumed on February 22 between 0600 and 0700 hrs and ended by 1500 hrs. Total precipitation at Rolla-UMR was 1.20 inches, and rainfall intensity was as high as 0.30 inches/hour, which was measured between 0700 and 0800. Light rain continued on February 23, but only added another 0.12 inches. On February 22, Salem also reported 1.20 inches of precipitation and an additional 0.27 inches on February 23. The three remote rain gage stations were not yet installed in Dry Fork watershed.

Discharge began increasing at Maramec Spring on February 22 between 1000 and 1100 hrs, about four to five hours after Rolla began reporting rain. Discharge was about 162 ft^3/sec at 1000 hrs. At 1100 hrs it was 171 ft^3/sec, and 190 ft^3/sec at 1200 hours. Flow peaked February 23 at 0200 hrs at 392 ft^3/sec, about 21 hours after precipitation began at Rolla and 12 hours after it ended.

The discharge increase at Maramec Spring following the precipitation was, of course, caused by groundwater recharge, but the arrival of the new recharge at Maramec Spring is not marked by the increase in discharge. The discharge peak following the rainfall occurred much too soon to be the water provided by the rainfall. Rather, the fresh recharge is signaled by a change in water quality at the spring. More specifically, a decrease in the amount of dissolved solids.

During dry weather, the water chemistry at Maramec Spring is very stable. The water temperature is essentially constant, and the amount of dissolved materials in the water increases very slowly as the spring derives water from storage, water whose contact time with rock in the aquifer is continuously increasing. When recharge from precipitation occurs, the water introduced into the spring system has a very low dissolved solids content. It begins dissolving material from the soluble bedrock, but it takes at least several weeks before the water dissolves its full mineral load. Until then, it has a substantially lower dissolved solids content, and thus a much lower specific conductance, than the pre-storm water in the system.

The recharge provided by precipitation occurring from February 19 through February 23 did not begin arriving at Maramec Spring until about 1900 hrs on February 23, nearly four days after the initial rain on February 19. Specific conductance was about 301 µS prior to the precipitation, and decreased to about 207 µS by 0400 hrs on March 1. The low point of the specific conductance shows the approximate center of the recharge mass, so its arrival was about 10 days after precipitation began, and about 7 days after it ended. By this time, discharge at Maramec Spring had decreased to 224 ft^3/sec. Figure 31 shows hourly precipitation at Rolla-UMR, and hourly discharge and specific conductance at Maramec Spring for late February and early March, 1994.

Rainfall in the Maramec Spring area during the summer and fall of 1994 was above normal. Between July and December, Rolla-UMR reported 23.6 inches of precipitation, about 2.43 inches above normal. Although July and August rainfalls were both above normal, September and October were fairly dry. Rainfall in September at Rolla-UMR was 1.20 inches below normal for that month; October was 0.74 inches below normal. Discharge at Maramec Spring decreased steadily from middle July through October. Three rainfall events in late August and early September, all containing more than an inch of precipitation, caused a very small discharge increases. Specific conductance increased steadily between late July and the end of October. The late August-early September rainfall caused a small decrease in specific conductance, but within a few days it began increasing again. The steady decline in discharge and increase in conductance between early September and the end of October show that there was very little groundwater recharge during this time period.

On November 3, light precipitation began falling at Rolla at about 0800 hrs. It continued until about 1300 hrs, and total rainfall during this five hour period was 0.04 inches. Precipitation resumed late that evening, and between 2300 hrs on November 3 and 0400 hrs November 4, there was 1.10 inches of rain. Rain resumed on November 4 at about 0900 hrs, and continued through the rest of the day and most of November 5, ending about 2300 hrs. Total precipitation for the period 0900 hrs November 3 through 2300 hrs November 5 at Rolla-UMR was 4.58 inches.

Precipitation began at Dry Fork #1 precipitation station about 1100 hrs on November 3. Here, only 0.07 inches of rain fell on November 3. On November 4, rainfall resumed at about 0200 hrs, and during the next four hours there was about 0.42 inches of rain. Precipitation resumed at about 1000 hrs, continued the remainder of the day, and ended November 5 at about 2200 hrs. Total rainfall here for the period 1100 hrs November 3 through 2200 hrs November 5 was 3.51 inches.

Less precipitation was recorded at Dry Fork #2 precipitation station than at the other sites. Here, between 1200 hrs and 2100 hrs November 3, there was 0.17 inches of rain. Precipitation resumed at about 0200 hrs on November 4, and continued through 2200 hrs on November 5. Total rainfall for the storm was 2.75 inches.

Between 1300 hrs and 2400 hrs on November 3, Dry Fork #3 precipitation station recorded 0.39 inches of rain. Rain resumed at about 0300 hrs on November 4 and ended about midnight on November 5. Total rainfall here between 1300 hrs November 3 and 2400 hrs November 5 was 3.75 inches. Precipitation at Salem during this same period was 3.55 inches, and it was even higher at Montauk, 4.17 inches.

During late October and early November, the discharge of Maramec Spring was well below average but typical for dry, fall weather. Immediately before precipitation began on November 3, discharge at Maramec Spring was about 114 ft^3/sec. Flow began increasing between 1400 hrs and 1500 hrs on November 4. The rain that fell

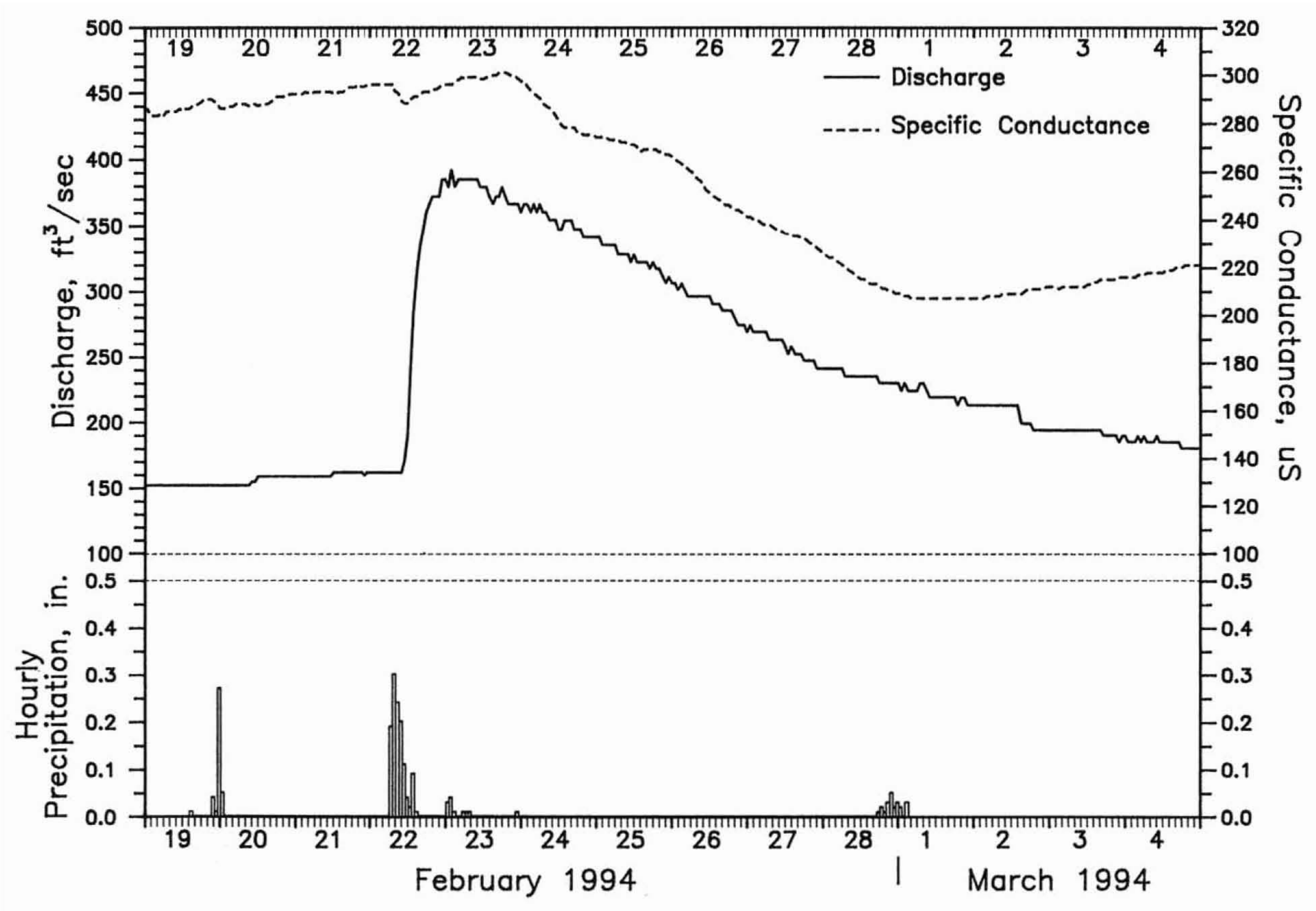


Figure 31. Hourly discharge and conductance at Maramec Spring, and hourly precipitation at Rolla-UMR, February 19 through March 4, 1994.

in the area on November 3 was probably too little to have resulted in any groundwater recharge. More likely, the flow increase at Maramec Spring that began on November 4 resulted from precipitation that began in the recharge area not more than 12 hours earlier. Flow peaked November 5 at 2200 hrs at 328 ft^3/sec, and decreased for the next four days until additional rainfall in the area caused another increase in flow.

Specific conductance at Maramec Spring immediately before rain began on November 3 was about 350 µS. It had been steadily increasing during most of September and October when the entire discharge of Maramec Spring was being derived from aquifer storage. Conductance began decreasing at about 0200 hrs on November 8 as the November 4 recharge began arriving at the spring. The first arrival of the new recharge was about 96 hours after heavy rainfall began on November 4. Conductance continued to decline until November 20 at 1700 hrs, about 16.5 days after recharge began, when it measured 256 µS. It rose slightly to 269 µS by November 22, and began dropping again, hitting bottom on November 30 at 256 µS. Figure 32 shows hourly precipitation at Rolla-UMR, and the three Dry Fork precipitation stations along with hourly discharge and specific conductance at Maramec Spring for this period.

December 1994 was a dry month in the Maramec Spring area. Rolla-UMR reported only 1.11 inches for the month. Dry Fork precipitation stations #1, #2, and #3 recorded 1.08 inches, 0.92 inches, and 1.26 inches, respectively. Salem and Montauk reported 1.43 inches and 1.47 inches. Early January 1995 also remained dry, until about midnight on January 12 when heavy rainfall began in the Maramec Spring area. Between 2300 hrs January 12 and 0600 hrs January 14, Rolla-UMR reported 2.83 inches of precipitation. Dry Fork stations #1 and #2 were out of service at this time, but at Dry Fork #3 there was 2.17 inches of rain during this period. Similar amounts were reported at Salem and Montauk, 2.26 inches and 2.03 inches, respectively. Hourly data from Rolla-UMR and Dry Fork #3 show that the heaviest precipitation occurred near the start of the storm, from about 2300 hrs January 12 to about 0500 hrs on January 13.

Prior to this precipitation event, discharge at Maramec Spring had been decreasing slightly but steadily for several weeks, measuring about 119 ft^3/sec when precipitation began on January 12. Discharge began increasing at 0100 hrs on January 13, only about 2 hours after rainfall began being recorded at Rolla-UMR and Dry Fork #3 (figure 33). It increased steadily for the next 26 hours and peaked well above 1,200 ft^3/sec at about 0500 on January 14. Stage heights above 2.5 ft at Maramec Spring have not been rated. At 2200 hrs on January 13, stage height at the spring was 2.39 ft, and discharge was about 1,261 ft3/sec. Stage height peaked at 3.67 ft at about 0500 hrs. The stage height was above the rating curve for about 15 hours on January 13 and 14. The Meramec River is not gaged near Maramec Spring, and it is difficult to know if part of the high-stage readings at the spring may have been due to backwater from the river. However, the specific conductance data indicates that there was no backwater effects from the Meramec River.

Specific conductance at Maramec Spring began dropping about 0700 hrs on January 14, about 32 hours after precipitation began. It decreased steadily over the next several days, from about 321 µS to a low of only 76 µS. Specific conductance did not begin decreasing until about 2 hours after the stage height had peaked. Had backwater from the river been affecting the spring, the conductance change would likely have began occurring several hours earlier. Also, when conductance began decreasing, the change was relatively smooth. A mixing of surface water with groundwater would likely have resulted in sharp fluctuations of conductivity rather than a smooth decline.

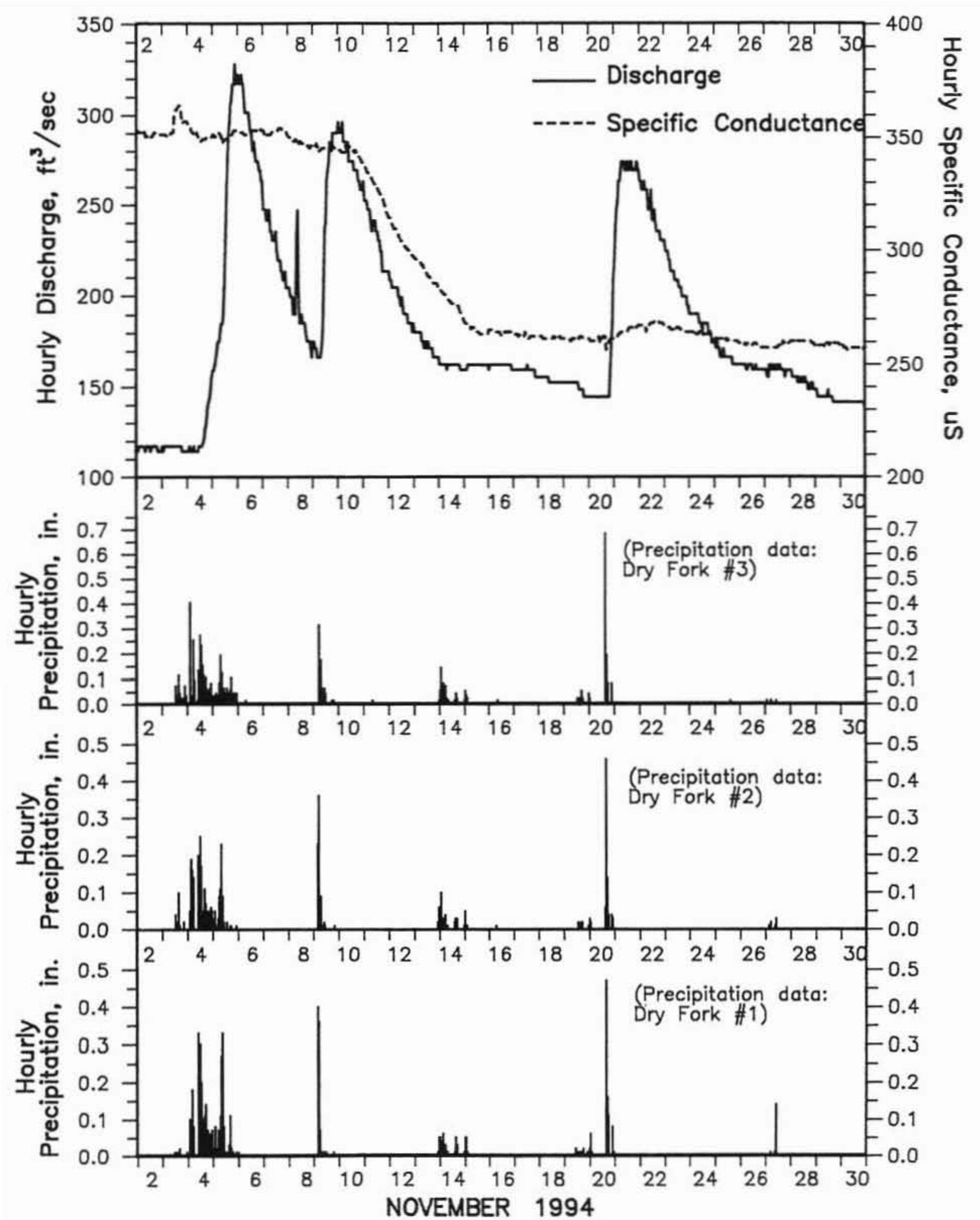


Figure 32. Hourly discharge and specific conductance at Maramec Spring, and hourly rainfall at Dry Fork #1, Dry Fork #2 and Dry Fork #3 precipitation stations, November 2 to November 30, 1994.

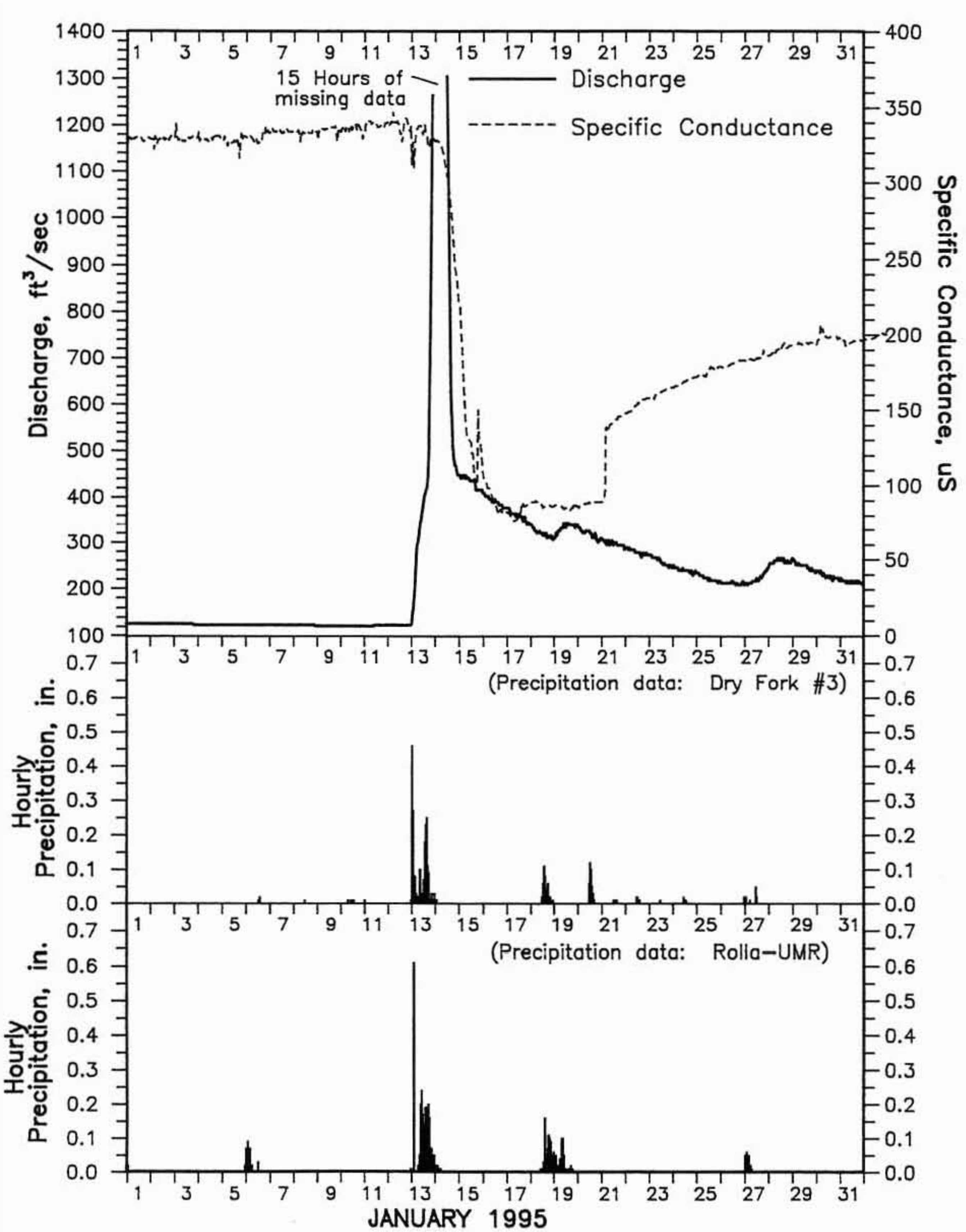


Figure 33. Hourly discharge and specific conductance at Maramec Spring, and hourly rainfall at Rolla-UMR and Dry Fork #3 precipitation stations, January 1995.

CONCLUSIONS

Dye tracing plus other hydrologic data show that Maramec Spring receives recharge from a 310 mi^2 area west and south of the spring. Flow data, field observations, and losing-stream characteristics indicate that a 52 mi^2 area of Norman Creek provides between 22.2 percent and 27 percent of the recharge for Maramec Spring. A 12 mi^2 area of Asher Hollow is estimated to provide between 5.1 percent and 6.3 percent of the recharge. Dry Fork basin upstream from Phelps County Route F, which contains about 246 mi^2, provides the remainder of the recharge, supplying from about 66.7 percent to 72.2 percent of the recharge for Maramec Spring.

Precipitation, discharge, and specific conductance data shows that the discharge of Maramec Spring responds quickly to precipitation in the recharge area. Discharge begins to increase within a few hours after heavy rainfall begins. Recharge supplied by heavy rainfall generally begins arriving at Maramec Spring a few days after the precipitation occurred, but the center of the recharge mass does not arrive at the spring until about 12 to 15 days after precipitation occurred.

Although yet to be proven by dye tracing, there is substantial evidence that water lost into the subsurface in upper Dry Fork watershed and the upper Meramec River watershed upstream of Missouri Highway 32 recharges springs outside of the watersheds. Data supporting this includes an earlier possible dye trace by Aley (1982), and flow characteristics of the Meramec River. Dye from several attempted traces has been lost in upper Dry Fork basin and the adjacent part of the Current River basin. Additional work will be necessary to unravel the complexities of the karst drainage system in this area.

The quality of water at Maramec Spring is a function of the composition of the rock it travels through as well as activities within its recharge area. Currently, the impact of contaminants on Maramec Spring's quality is low, as evidenced by overall good water quality. Bacteria including fecal coliform and fecal streptococci is regularly present in the spring water, but nutrients such as nitrate and phosphate are low and do not appear to have increased substantially for more than 50 years. A steady increase in nutrients from organic wastes could cause a lowering of dissolved oxygen as well as increased algae at the spring. Catastrophic water-quality problems, however, are not likely to occur unless large quantities of contaminants are introduced over a short period.

It was beyond the scope of this study to make a detailed assessment of potential water-quality risks in the recharge area of Maramec Spring. Obviously, there are numerous potential contaminant sources, including gasoline stations, petroleum storage sites, agricultural chemical suppliers, wood treating operations, sawmills, private liquid-waste disposal systems, agricultural lagoons, feed lots, an anhydrous ammonia pipeline, numerous highways, and a host of others.

Each of these present a finite risk to groundwater quality, but the risk is difficult

to assess because it is impossible to predict accidental releases. However, it is safe to assume that a some point in time an environmental accident will occur. The effects it will have on groundwater quality will depend mostly on the physical and chemical characteristics of the contaminant, the volume of contaminant that was released, and the hydrogeologic characteristics of the site where the contaminant was released. The November 1981 pipeline leak that severely affected water quality at Maramec Spring occurred along a losing stream. Had the leak occurred in an upland setting away from major groundwater conduits, the effects would likely have been different than those observed. Water quality at Maramec Spring would probably not have been as badly affected because the fertilizer would not have arrived en masse, but the spring would likely have been affected much longer as the contaminants moved more slowly through the groundwater system. Private water-supply wells would have been at greater risk if the spill was in a diffuse recharge setting where groundwater is not as well confined to conduit flow paths.

Water quality at Maramec Spring cannot be controlled at the mouth of the spring, it is dependant upon activities taking place within its 310 square mile recharge area. Only the landowners and residents in the recharge area, through wise decisions concerning land use, the level of development, and the safe disposal of wastes, can ensure the continued quality of water at Maramec Spring.

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APPENDIX

APPENDIX 1
DAILY PRECIPITATION DATA, 1994 AND 1995, MARAMEC SPRING AREA.

Annual Summary, 1994, Dry Fork #1 Precipitation Station

Phelps County, NE 1/4 SE 1/4 SEC. 4, T. 36 N., R. 7 W.
37° 52' 06" north latitude, 91° 41' 20" west longitude
Land surface elevation: 1070 feet above mean sea level
Weather observer: DNR-DGLS
Installation operated by: DNR-DGLS
Type of installation: Tipping bucket rain gage and digital recorder
Station installed March 30, 1994

Note: **** Denotes missing data

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	****	****	****	....	....	....	....	....	0.01	....	....	....
2	****	****	****	0.05	....	0.04	....	0.28	....	....	....	....
3	****	****	****	0.05	....	....	....	....	....	....	0.07	0.04
4	****	****	****	....	....	0.04	....	0.02	0.13	....	2.15	....
5	****	****	****	0.68	....	0.09	....	....	1.18	....	1.28	0.01
6	****	****	****	0.07	0.18	0.19	3.23	....	....	....	0.01	0.09
7	****	****	****	....	0.45	....	0.48	....	....	0.04	....	....
8	****	****	****	....	....	0.44	0.31	....	....	1.19	....	0.17
9	****	****	****	0.62	....	....	....	0.66	....	0.01	0.88	0.13
10	****	****	****	3.67	....	0.01	....	....	....	....	....	....
11	****	****	****	1.27	....	....	....	....	....	....	....	....
12	****	****	****	****	0.17	....	....	....	....	0.16	....	....
13	****	****	****	****	0.07	....	0.04	....	....	0.03	0.06	....
14	****	****	****	****	1.06	....	0.01	0.60	....	....	0.33	....
15	****	****	****	****	....	....	....	....	....	0.01	0.11	....
16	****	****	****	****	....	....	0.40	....	....	0.01	....	0.41
17	****	****	****	****	....	....	....	....	....	0.01	....	....
18	****	****	****	****	....	....	....	....	....	0.86	....	....
19	****	****	****	****	....	....	....	0.02	....	0.01	0.10	....
20	****	****	****	....	....	....	0.56	0.53	....	....	0.92	0.19
21	****	****	****	0.48	....	....	0.87	....	0.01	....	....	....
22	****	****	****	0.04	....	....	....	....	0.03	....	....	....
23	****	****	****	....	....	0.11	....	....	0.45	....	....	....
24	****	****	****	....	....	0.02	....	....	0.30	....	....	....
25	****	****	****	....	0.72	0.22	....	....	....	....	....	....
26	****	****	****	0.25	....	0.99	....	0.06	....	....	....	....
27	****	****	****	0.20	....	....	....	0.01	....	....	0.16	....
28	****	****	****	3.20	....	0.37	....	....	....	....	....	....
29	****	——	****	1.11	1.66	....	....	1.28	....	....	....	....
30	****	——	....	0.59	0.27	....	....	1.44	....	....	....	....
31	****	——	....	——	....	——	....	0.05	——	0.23	——	0.04
Monthly Totals	****	****	****	12.28*	4.58	2.52	5.90	4.95	2.11	2.56	6.07	1.08

Total rainfall, March 30 to December 31, 42.05 inches

Appendix 1 (continued)

Annual Summary, 1995, Dry Fork #1 Precipitation Station

Phelps County, NE 1/4 SE 1/4 SEC. 4, T. 36 N., R. 7 W.
37° 52' 06" north latitude, 91° 41' 20" west longitude
Land surface elevation: 1070 feet above mean sea level
Weather observer: DNR-DGLS
Note: **** Denotes missing data
Installation operated by: DNR-DGLS
Type of installation: Tipping bucket rain gage and digital recorder
Station installed in 1995, 1 year of data

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	....	****	****	0.03	1.31	0.09	....	....	....	....	0.09	....
2	0.01	****	****	....	....	....	....	0.27	....	0.14	0.02	....
3	....	****	****	0.15	0.16	....	0.45	....	1.06	0.36	....	....
4	....	****	****	....	0.10	....	0.19	0.47	0.24	....	....	....
5	....	****	****	....	....	0.64	0.02	....	....	....	0.10	....
6	....	****	****	....	0.11	0.02	0.58	0.49	....	....	0.04	....
7	....	****	****	....	....	0.36	....	0.11	0.37	....	0.01	....
8	0.01	****	****	....	0.84	0.73	1.02	....	0.01	....	....	....
9	****	****	****	....	0.01	0.59	....	....	....	....	....	....
10	****	****	****	1.79	....	0.93	....	0.02	....	0.49	1.06	....
11	****	****	....	0.25	0.02	0.21	....	....	....	....	0.02	0.06
12	****	****	....	0.04	0.04	....	....	....	....	....	0.35	0.03
13	****	****	....	....	....	....	....	....	....	0.01	0.02	....
14	****	****	....	....	....	0.13	....	0.84	....	....	....	....
15	****	****	....	....	....	....	....	0.01	0.02	....	0.16	0.57
16	****	****	....	....	0.18	....	....	0.01	0.39	....	....	....
17	****	****	....	0.58	4.28	....	....	....	....	....	....	0.27
18	****	****	....	0.20	1.12	0.81	....	....	....	....	....	0.21
19	****	****	....	0.18	....	....	....	....	0.40	0.65	....	1.60
20	****	****	0.05	1.48	....	....	0.34	....	0.01	....	....	....
21	****	****	....	0.38	....	....	....	....	0.03	....	....	....
22	****	****	....	....	....	....	....	....	....	....	....	....
23	****	****	....	0.74	....	0.69	0.30	....	....	....	....	....
24	****	****	....	0.10	0.27	0.02	....	....	....	....	....	....
25	****	****	0.11	0.01	0.55	0.38	0.06	....	....	....	....	0.08
26	****	****	1.45	0.20	0.55	0.85	0.04	....	....	0.32	....	....
27	****	****	0.01	....	0.44	0.02	....	....	....	....	....	0.27
28	****	****	....	....	....	0.13	....	....	....	....	....	....
29	****	——	....	1.04	....	....	....	....	....	....	....	0.03
30	****	——	....	0.06	....	....	....	....	0.08	0.34	....	0.02
31	****	——	....	——	0.21	——	....	....	——	....	——	0.09
Monthly Totals	0.02*	****	1.62*	7.23	10.19	6.60	3.00	2.22	2.61	2.31	1.87	3.23

Total yearly rainfall: 40.90 inches*

Appendix 1 (continued)

Annual Summary, 1994, Dry Fork #2 Precipitation Station

Dent County, NE 1/4 SE 1/4 SEC. 13, T. 35 N., R. 7 W.
37° 45' 12" north latitude, 91° 38' 24" west longitude
Land surface elevation: 1155 feet above mean sea level
Weather observer: DNR-DGLS
Note: **** Denotes missing data
Installation operated by: DNR-DGLS
Type of installation: Tipping bucket rain gage and digital recorder
Station installed June 23, 1994

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	****	****	****	****	****	****	....	....	0.02	....	....	....
2	****	****	****	****	****	****	....	0.04	....	....	....	....
3	****	****	****	****	****	****	....	....	....	....	0.13	0.01
4	****	****	****	****	****	****	....	0.01	0.01	....	1.85	....
5	****	****	****	****	****	****	....	....	0.84	....	0.73	0.01
6	****	****	****	****	****	****	1.19	....	....	....	....	0.10
7	****	****	****	****	****	****	0.38	0.01	....	....	....	....
8	****	****	****	****	****	****	0.27	....	....	0.85	....	0.30
9	****	****	****	****	****	****	....	0.01	0.01	....	0.83	0.07
10	****	****	****	****	****	****	....	....	....	....	....	....
11	****	****	****	****	****	****	....	....	....	....	....	....
12	****	****	****	****	****	****	....	....	....	0.14	....	....
13	****	****	****	****	****	****	....	....	....	0.02	0.08	....
14	****	****	****	****	****	****	0.03	1.04	....	....	0.35	....
15	****	****	****	****	****	****	....	....	....	....	0.07	....
16	****	****	****	****	****	****	1.01	....	....	....	0.01	0.23
17	****	****	****	****	****	****	....	....	....	....	....	0.01
18	****	****	****	****	****	****	....	....	....	0.72	....	....
19	****	****	****	****	****	****	....	0.01	....	....	0.09	0.07
20	****	****	****	****	****	****	1.00	0.54	....	....	0.82	0.09
21	****	****	****	****	****	****	1.06	....	....	....	....	....
22	****	****	****	****	****	****	....	0.01	0.04	....	....	....
23	****	****	****	****	****	0.18	....	....	0.28	....	....	....
24	****	****	****	****	****	0.01	....	....	0.23	0.01	....	....
25	****	****	****	****	****	0.10	....	....	....	....	....	....
26	****	****	****	****	****	1.24	....	0.16	....	....	....	....
27	****	****	****	****	****	....	....	....	0.01	....	0.08	....
28	****	****	****	****	****	0.56	....	....	....	....	....	....
29	****	——	****	****	****	....	....	0.49	....	....	....	....
30	****	——	****	****	****	....	0.06	1.13	....	....	....	....
31	****	——	****	——	****	——	....	0.04	——	0.16	——	0.03
Monthly Totals	****	****	****	****	****	2.09*	5.00	3.49	1.44	1.90	5.04	0.92

Total rainfall, June 23 to December 31: 19.88 inches*

Appendix 1 (continued)

Annual Summary, 1995, Dry Fork #2 Precipitation Station

Dent County, NE 1/4 SE 1/4 SEC. 13, T. 35 N., R. 7 W.
37° 45' 12" north latitude, 91° 38' 24" west longitude
Land surface elevation: 1155 feet above mean sea level
Weather observer: DNR-DGLS Note: **** Denotes missing data
Installation operated by: DNR-DGLS
Type of installation: Tipping bucket rain gage and digital recorder
Station installed in 1994, 1 Year of data

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.01	****	....	....	1.07	....	....	....	....	****	****	****
2	....	****	....	....	....	0.01	....	0.13	....	****	****	****
3	....	****	0.05	0.11	0.11	....	0.58	....	1.22	****	****	****
4	....	****	0.06	0.01	0.11	....	0.11	0.01	0.44	****	****	****
5	....	****	....	....	....	....	0.02	....	....	****	****	****
6	0.01	....	0.62	....	0.10	0.03	0.44	0.40	....	****	****	****
7	****	....	1.29	....	0.02	0.30	....	0.06	0.17	****	****	****
8	****	....	0.01	....	0.79	1.00	0.71	....	0.04	****	****	****
9	****	....	....	....	....	0.75	....	....	....	****	****	****
10	****	....	....	1.35	0.01	0.65	....	....	....	****	****	****
11	****	....	....	0.18	0.06	0.15	....	....	....	****	****	****
12	****	....	....	0.02	....	....	....	....	....	****	****	****
13	****	....	....	....	0.02	....	....	....	....	****	****	****
14	****	0.09	....	....	....	....	....	0.09	....	****	****	****
15	****	0.12	....	....	....	....	....	....	0.04	****	****	****
16	****	....	....	....	0.17	....	....	....	0.19	****	****	****
17	****	....	....	0.27	1.66	....	0.04	....	....	****	****	****
18	****	....	....	0.14	0.42	....	....	....	....	****	****	****
19	****	....	....	0.19	0.01	....	....	....	0.53	****	****	****
20	****	....	0.19	0.88	....	....	0.13	....	0.02	****	****	****
21	****	....	....	0.28	....	....	....	....	0.10	****	****	****
22	****	....	....	....	0.01	....	....	....	****	****	****	****
23	****	....	....	0.61	....	0.07	0.44	....	****	****	****	****
24	****	....	....	0.14	0.66	0.13	0.02	....	****	****	****	****
25	****	....	0.07	....	0.01	0.20	0.24	....	****	****	****	****
26	****	0.42	0.66	0.09	0.52	0.10	....	....	****	****	****	****
27	****	0.21	....	....	0.46	....	....	....	****	****	****	****
28	****	0.01	....	....	....	0.33	....	....	****	****	****	****
29	****	——	....	0.80	....	....	....	....	****	****	****	****
30	****	——	....	0.17	....	0.02	....	....	****	****	****	****
31	****	——	....	——	0.24	——	....	0.01	——	****	——	****
Monthly Totals	0.02*	0.85*	2.95	5.24	6.45	3.74	2.73	0.70	2.75*	****	****	****

Total yearly rainfall: 25.43 inches*

Appendix 1 (continued)

Annual Summary, 1994, Dry Fork #3 Precipitation Station

Dent County, SE 1/4 SW 1/4 SEC. 28, T. 34 N., R. 7 W.
37° 36' 59" north latitude, 91° 42' 46" west longitude
Land surface elevation: 1195 Feet above mean sea level
Weather observer: DNR-DGLS Note: **** Denotes missing data
Installation operated by: DNR-DGLS
Type of installation: Tipping bucket rain gage and digital recorder
Station installed June 27, 1994

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	****	****	****	****	****	****	....	0.02	****	....	....	....
2	****	****	****	****	****	****	....	0.12	****	....	....	....
3	****	****	****	****	****	****	....	....	....	0.03	0.39	0.02
4	****	****	****	****	****	****	....	....	....	0.01	2.15	....
5	****	****	****	****	****	****	....	....	1.31	....	1.26	....
6	****	****	****	****	****	****	0.24	....	....	....	....	0.15
7	****	****	****	****	****	****	0.34	....	....	....	....	....
8	****	****	****	****	****	****	0.16	....	....	0.93	....	0.42
9	****	****	****	****	****	****	....	....	....	....	0.16	0.09
10	****	****	****	****	****	****	....	....	0.01	....	....	....
11	****	****	****	****	****	****	....	....	....	....	0.01	....
12	****	****	****	****	****	****	....	....	0.01	0.17	....	....
13	****	****	****	****	****	****	....	....	....	0.04	....	....
14	****	****	****	****	****	****	0.25	0.11	....	....	0.48	....
15	****	****	****	****	****	****	....	....	....	....	0.11	....
16	****	****	****	****	****	****	1.07	....	....	....	0.01	0.24
17	****	****	****	****	****	****	....	....	....	....	....	0.01
18	****	****	****	****	****	****	....	....	....	0.90	....	....
19	****	****	****	****	****	****	....	0.01	....	....	0.13	0.07
20	****	****	****	****	****	****	1.04	****	....	....	1.09	0.18
21	****	****	****	****	****	****	0.35	****	0.01	0.04	....	....
22	****	****	****	****	****	****	0.01	****	0.06	....	....	....
23	****	****	****	****	****	****	....	****	0.27	....	....	....
24	****	****	****	****	****	****	....	****	0.22	0.10	....	....
25	****	****	****	****	****	****	....	****	....	....	0.01	....
26	****	****	****	****	****	****	0.01	****	0.01	....	....	....
27	****	****	****	****	****	....	....	****	....	....	0.03	....
28	****	****	****	****	****	0.27	....	****	....	....	....	....
29	****	——	****	****	****	....	....	****	....	....	....	....
30	****	——	****	****	****	....	....	****	....	....	....	....
31	****	——	****	——	****	——	....	****	——	0.26	——	0.08
Monthly Totals	****	****	****	****	****	0.27*	3.47	0.26*	1.90	2.48	5.83	1.26

Total rainfall, June 26 to December 31, 15.47 inches

Appendix 1 (continued)

Annual Summary, 1995, Dry Fork #3 Precipitation Station

Dent County, SE 1/4 SW 1/4 SEC. 28, T. 34 N., R. 7 W.
37° 36' 59" north latitude, 91° 42' 46" west longitude
Land surface elevation: 1195 feet above mean sea level
Weather observer: DNR-DGLS Note: **** Denotes missing data
Installation operated BY: DNR-DGLS
Type of installation: Tipping bucket rain gage and digital recorder
Station installed in 1994, 1 year of data

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	....	....	....	0.01	1.07	0.18	....	....	....	....	0.16	****
2	....	0.13	0.01	....	....	0.01	....	0.03	....	0.27	0.02	****
3	....	0.23	0.07	0.09	0.32	....	1.07	....	0.02	0.09	....	****
4	....	....	0.06	....	0.19	....	0.20	....	0.15	....	....	****
5	....	....	....	....	0.01	0.05	0.03	....	....	....	0.04	****
6	0.03	....	1.04	....	0.13	0.08	0.47	0.39	....	....	0.08	****
7	....	0.03	1.96	....	....	....	....	0.23	0.11	....	0.02	****
8	0.01	....	0.01	....	0.49	0.36	0.24	0.01	0.02	....	....	****
9	....	....	....	....	....	0.69	....	0.96	0.01	....	....	****
10	0.04	....	....	1.84	....	0.78	....	0.04	....	0.04	1.01	****
11	0.01	....	....	0.23	....	0.13	....	....	....	....	0.07	****
12	0.01	....	....	....	....	....	....	....	....	....	0.19	****
13	2.15	....	....	....	....	....	....	....	0.46	0.14	0.03	****
14	0.01	....	....	....	....	....	....	....	....	....	....	****
15	....	0.12	....	....	....	....	....	....	0.07	....	0.16	****
16	....	....	....	....	0.28	....	....	....	0.19	....	****	****
17	....	....	....	0.29	1.14	....	....	....	....	....	****	****
18	0.43	....	....	0.30	0.31	....	....	....	....	....	****	****
19	....	....	....	0.28	....	....	....	....	0.51	0.59	****	****
20	0.37	....	0.08	1.02	....	....	....	....	0.02	0.01	****	****
21	0.03	....	....	0.32	0.03	....	....	....	0.09	....	****	****
22	0.06	....	....	....	....	....	....	....	....	....	****	****
23	0.01	....	....	0.61	....	0.21	0.60	....	....	0.01	****	****
24	0.04	....	....	....	0.03	0.15	0.02	....	....	....	****	****
25	....	....	0.05	....	0.01	0.02	0.02	....	....	....	****	****
26	0.02	0.66	0.68	0.14	0.01	0.37	0.02	....	....	0.41	****	****
27	0.10	0.33	....	....	....	....	....	....	....	....	****	****
28	....	....	....	....	....	0.22	....	....	....	....	****	****
29	....	——	....	0.81	....	....	....	....	....	0.01	****	****
30	....	——	....	0.31	....	0.05	....	....	0.44	0.49	****	****
31	....	——	....	——	....	——	....	0.29	——	....	——	****
Monthly Totals	3.32	1.50	3.96	6.25	4.02	3.30	2.67	1.95	2.09	2.06	1.78	****

Total yearly rainfall, January 1 to December 16, 32.90 inches

Appendix 1 (continued)

Annual Summary, 1994, Rolla-UMR Weather Observation Station

Phelps County, NE 1/4 SW 1/4 SEC. 2, T. 37 N., R. 8 W.
37° 57' 23" north latitude, 91° 46' 33" west longitude
Land surface elevation: 1165 Feet above mean sea level
Weather observer: A. C. Spreng-UMR Geology Department
Installation operated by: National Weather Service
Type of installation: NWS recording rain gage
Station installed in 1882, 112 years of data

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	....	....	0.05	....	....	....	....	....	0.02	....	....	....
2	0.03	....	....	0.09	....	0.01	0.16	0.54	....	....	....	....
3	0.07	....	....	0.03	....	0.12	....	0.17	....	....	0.55	0.01
4	....	....	....	....	....	0.35	....	0.09	0.10	....	2.17	....
5	....	....	....	0.83	....	....	....	....	1.35	....	1.86	....
6	0.02	....	....	0.06	0.33	0.23	1.05	....	....	....	....	0.15
7	0.01	....	0.35	....	0.24	....	2.37	....	....	0.11	....	....
8	....	....	0.06	....	....	0.58	0.20	....	....	1.14	....	0.15
9	....	0.05	....	0.90	....	0.02	....	0.03	....	....	0.79	0.04
10	0.19	....	....	2.55	....	0.04	....	....	....	....	....	....
11	....	....	....	1.64	....	....	....	....	....	....	....	....
12	....	....	....	0.07	0.10	....	....	....	....	0.09	....	....
13	....	....	0.04	....	0.15	....	0.14	....	....	0.12	0.14	....
14	....	....	....	....	0.43	....	....	0.54	....	....	0.26	....
15	....	....	....	0.57	....	....	....	....	....	0.01	....	0.01
16	1.05	....	....	....	....	0.26	0.24	....	....	0.01	....	0.36
17	....	....	0.04	....	....	....	....	....	....	....	....	....
18	....	....	0.08	....	....	....	....	....	....	1.37	....	....
19	....	0.33	....	....	....	....	....	0.03	....	....	0.09	0.01
20	....	0.05	....	....	....	....	0.51	0.30	....	....	1.25	0.35
21	....	....	....	....	....	....	0.65	....	0.01	....	....	....
22	....	1.20	....	....	....	....	....	....	0.07	....	....	....
23	....	0.12	....	....	....	....	....	....	0.43	....	....	....
24	0.02	....	....	....	....	0.93	....	....	0.35	....	....	....
25	0.05	....	....	....	0.36	0.15	....	....	....	....	....	....
26	0.15	....	1.12	0.40	....	1.50	....	....	0.02	....	0.02	....
27	....	....	....	0.22	....	....	0.02	....	....	....	....	....
28	....	0.17	0.23	2.80	....	0.50	....	....	....	....	....	....
29	....	——	....	0.78	0.17	....	....	1.30	....	....	....	....
30	0.04	——	....	0.54	0.34	....	....	1.48	....	....	....	....
31	....	——	....	——	....	——	....	0.04	——	0.30	——	0.03
Monthly Totals	1.63	1.92	1.97	11.48	2.12	4.69	5.34	4.52	2.35	3.15	7.13	1.11

Total yearly rainfall: 47.41 inches

Appendix 1 (continued)

Annual Summary, 1995, Rolla-UMR Weather Observation Station

Phelps County, NE 1/4 SW 1/4 SEC. 2, T. 37 N., R. 8 W.
37° 57' 23" north latitude, 91° 46' 33" west longitude
Land surface elevation: 1165 feet above mean sea level
Weather observer: A. C. Spreng-UMR Geology Department
Installation operated by: National Weather Service
Type of installation: NWS recording rain gage
Station installed in 1882, 113 years of data

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NO	DEC
1	0.04	....	0.02	0.03	1.33	0.09	....	....	....	....	0.14	....
2	....	....	0.04	....	....	....	....	1.40	....	0.17	....	....
3	....	0.55	....	0.17	0.30	....	0.40	0.01	0.55	0.15	....	....
4	....	....	0.05	....	0.12	....	0.09	0.67	0.51	....	....	....
5	0.02	....	....	....	....	....	0.01	....	....	....	0.12	....
6	0.37	0.01	0.60	....	0.10	0.01	1.80	0.15	0.32	....	0.05	....
7	....	0.06	1.22	....	....	0.21	....	0.18	0.01	....	....	....
8	....	....	....	....	0.63	1.26	0.71	....	....	....	....	0.26
9	....	....	....	....	....	1.08	....	....	0.01	....	....	....
10	....	....	....	1.86	....	0.70	....	....	....	0.39	1.17	....
11	....	....	....	0.38	0.03	0.13	....	....	....	....	0.06	....
12	0.01	....	....	0.07	0.83	....	....	....	....	....	0.30	....
13	2.74	....	....	....	....	....	....	....	....	0.09	....	....
14	0.08	0.07	....	....	....	....	....	0.12	....	....	....	....
15	....	0.07	....	....	....	....	....	0.03	....	....	0.12	0.68
16	....	....	....	0.06	0.33	....	....	0.01	0.09	....	....	....
17	....	....	....	0.26	3.55	....	....	....	....	....	....	0.28
18	0.78	....	....	....	0.77	....	....	....	....	....	....	1.45
19	0.56	....	....	0.16	....	....	....	....	0.43	0.89	....	1.55
20	....	....	0.08	0.69	....	....	0.14	....	....	....	....	....
21	....	....	....	0.30	....	....	....	....	0.04	....	....	....
22	....	....	....	....	....	....	....	....	....	....	....	....
23	....	....	....	0.66	0.15	....	0.47	....	....	....	....	....
24	....	....	....	0.16	0.37	0.24	0.07	....	....	....	....	....
25	....	....	0.06	....	0.28	0.07	....	....	....	....	....	....
26	....	0.67	2.65	....	0.32	1.96	0.15	....	....	0.23	....	....
27	0.26	0.30	....	0.12	0.39	....	....	....	....	....	....	....
28	....	0.01	....	....	0.01	....	....	....	....	....	....	....
29	....	——	....	1.23	....	....	....	....	....	....	....	....
30	....	——	....	....	....	....	....	....	0.26	0.33	....	0.03
31	....	——	....	——	....	——	....	....	——	....	——	....
Monthly Totals	4.86	1.74	4.72	6.15	9.51	5.75	3.84	2.57	2.22	2.25	1.96	4.25

Total yearly rainfall: 49.82 inches

Appendix 1 (continued)

Annual Summary, 1994, Montauk State Park Precipitation Station

Dent County, SW 1/4 SW 1/4 SEC. 23, T. 32 N., R. 7 W.
37° 27' 09" north latitude, 91° 40' 55" west longitude
Land surface elevation: 920 feet above mean sea level
Weather observer: DNR-Montauk State Park
Installation operated by: Missouri Department of Natural Resources
Type of installation: NWS nonrecording rain gage
Date of station installation not available

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	....	....	....	....	....	....	....	....	0.09	....	....	....
2	....	....	....	....	....	....	....	....	....	....	....	....
3	....	....	....	....	....	0.13	0.29	0.13	....	....	....	....
4	....	....	....	....	....	0.02	....	....	....	....	1.26	....
5	....	....	....	0.62	....	....	....	....	1.40	....	....	....
6	....	....	....	0.73	....	....	....	....	....	....	2.91	....
7	....	....	0.78	....	1.60	2.21	0.21	....	....	....	....	....
8	....	....	0.08	....	....	....	0.32	....	....	0.14	....	....
9	....	0.05	0.52	....	....	0.80	....	....	....	0.93	....	0.62
10	....	....	....	1.58	....	....	....	....	....	....	0.89	....
11	0.25	....	....	1.36	....	0.04	....	....	....	....	....	....
12	....	....	....	1.10	....	....	....	0.32	....	....	....	....
13	....	....	....	....	....	....	....	....	....	0.15	....	....
14	....	....	0.03	....	....	....	0.03	0.15	....	....	0.62	....
15	....	....	....	0.46	....	....	....	....	....	....	0.15	....
16	....	....	....	....	....	....	....	....	....	....	....	0.38
17	0.85	....	....	....	....	0.10	0.90	....	....	....	....	....
18	....	....	0.11	....	....	....	....	....	....	....	....	....
19	....	0.81	....	....	....	0.40	....	....	....	1.17	....	0.16
20	....	....	....	....	....	....	1.00	....	....	....	....	0.31
21	....	....	....	....	....	0.03	....	0.66	....	....	1.03	....
22	....	0.72	....	0.55	....	....	0.10	....	0.13	....	....	....
23	....	0.76	....	....	....	....	....	....	....	....	....	....
24	....	....	....	....	....	0.30	....	....	0.23	0.18	....	....
25	....	....	....	0.49	0.20	....	....	....	....	....	....	....
26	....	....	1.28	0.13	....	0.77	....	....	....	....	....	....
27	0.83	....	....	....	....	....	....	0.79	....	....	....	....
28	0.08	....	....	1.65	....	0.48	....	....	....	....	....	....
29	....	——	....	1.42	....	....	....	0.13	....	....	....	....
30	....	——	....	1.91	1.72	....	....	....	....	....	....	....
31	....	——	....	——	....	——	....	2.27	——	0.18	——	....
Monthly Totals	2.01	2.34	2.80	12.00	3.52	5.28	2.85	4.45	1.85	2.75	6.86	1.47

Total yearly rainfall: 48.18 inches

Appendix 1 (continued)

Annual Summary, 1995, Montauk State Park Precipitation Station

Dent County, SW 1/4 SW 1/4 SEC. 23, T. 32 N., R. 7 W.
37° 27' 09" north latitude, 91° 40' 55" west longitude
Land surface elevation: 920 feet above mean sea level
Weather observer: DNR-Montauk State Park
Installation operated by: Missouri Department of Natural Resources
Type of installation: NWS nonrecording rain gage
Date of station installation not available

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	....	....	0.05	....	1.39	0.11	....	....	1.14	0.05	....	....
2	....	....	....	....	0.28	0.15	....	....	....	....	0.17	....
3	....	0.05	0.03	....	0.12	0.05	0.28	0.73	0.11	0.83	....	....
4	....	....	....	....	0.16	....	0.98	....	0.15	....	....	....
5	....	....	0.02	....	....	....	0.33	0.03	....	....	....	....
6	0.50	....	....	....	....	0.65	0.63	....	....	....	....	....
7	....	0.14	2.25	....	0.12	....	....	0.41	0.06	....	....	....
8	....	....	0.03	....	0.66	....	0.18	....	....	....	....	....
9	....	....	....	....	0.02	0.52	....	....	....	....	....	0.26
10	....	....	....	....	....	1.35	....	0.37	....	....	....	....
11	0.03	....	....	1.49	....	0.32	....	....	....	....	0.52	....
12	....	....	....	0.21	....	0.14	....	....	0.02	....	....	....
13	0.71	....	....	....	0.02	....	....	....	....	....	0.21	....
14	1.32	....	....	....	0.02	....	....	....	....	....	....	0.01
15	....	0.43	....	....	....	....	....	....	....	....	0.13	....
16	....	0.14	....	....	0.29	....	....	....	....	....	....	1.05
17	0.01	....	....	....	0.84	....	....	....	0.40	....	....	....
18	....	....	....	0.30	0.21	....	....	....	0.38	....	....	1.16
19	....	....	....	....	....	....	....	....	....	....	....	1.38
20	1.21	....	....	1.24	....	....	....	....	....	0.41	....	0.14
21	....	....	....	....	....	....	0.03	....	0.65	....	....	....
22	....	....	....	0.25	0.05	....	....	....	....	....	....	....
23	....	....	....	0.25	....	....	0.02	....	....	....	....	....
24	....	....	....	0.26	....	0.58	0.53	....	....	....	....	0.01
25	....	....	....	....	1.64	0.19	....	....	....	....	....	....
26	....	....	....	....	....	0.05	0.69	....	....	....	....	....
27	0.06	1.48	....	0.12	0.58	0.51	....	....	....	0.80	....	....
28	....	....	....	....	1.96	0.03	....	....	....	....	....	....
29	....	——	....	....	....	0.08	....	....	....	....	....	....
30	0.10	——	....	0.88	....	0.04	....	....	0.05	....	....	0.18
31	....	——	....	——	....	——	....	....	——	0.55	——	....
Monthly Totals	3.94	2.24	2.38	5.00	8.36	4.77	3.67	1.54	2.96	2.64	1.03	4.19

Total yearly rainfall: 42.72 Inches

Appendix 1 (continued)

Annual Summary, 1994, Salem Weather Observation Station

Dent County, SE 1/4 NE 1/4 SEC. 24, T. 34 N., R. 6 W.
37° 38' 01" north latitude, 91° 32' 10" west longitude
Land surface elevation: 1205 feet above mean sea level
Weather observer: National Forest Service, Mark Twain National Forest
Installation operated by: National Weather Service
Type of installation: NWS recording rain gage
Station installed in 1899, 95 years of data

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	....	....	0.30	....	0.01	....	....	....	0.02	....	0.03	....
2	....	....	....	....	....	....	....	....	....	....	....	....
3	0.19	....	....	0.12	....	1.79	....	....	....	....	0.04	0.03
4	0.01	....	....	....	....	1.03	....	....	....	0.06	1.53	....
5	....	....	....	0.72	....	....	....	....	1.15	....	1.98	....
6	....	....	....	0.26	0.02	....	....	....	....	....	0.07	....
7	....	....	0.47	....	0.28	0.72	0.13	....	....	....	....	0.05
8	....	....	0.05	....	....	0.67	0.73	....	....	1.35	....	0.14
9	....	0.05	0.28	....	....	....	....	....	....	0.25	1.11	0.39
10	0.02	....	....	1.85	....	....	....	0.06	....	....	0.01	....
11	0.07	....	....	1.79	....	....	....	....	....	....	....	....
12	0.02	....	....	1.24	0.08	....	....	....	....	....	....	....
13	....	....	0.01	....	0.03	....	....	....	....	0.20	....	....
14	0.01	....	....	....	0.35	....	....	0.53	....	....	0.56	....
15	....	....	....	0.60	1.05	....	0.85	....	....	0.01	0.11	....
16	0.09	....	....	....	....	....	0.21	....	....	....	....	0.26
17	0.80	....	....	....	....	0.48	0.39	....	....	....	....	....
18	....	....	0.15	....	....	....	....	....	....	0.04	....	....
19	....	....	....	....	....	0.15	....	....	....	1.31	....	....
20	....	0.74	....	....	....	....	....	0.75	....	....	0.12	0.43
21	....	....	....	0.03	....	....	1.83	....	....	....	0.95	0.05
22	....	1.20	....	0.46	....	....	0.16	....	0.10	0.03	....	....
23	....	0.27	....	....	....	0.16	....	....	....	....	....	....
24	....	0.02	....	....	....	0.53	....	....	0.63	0.03	....	....
25	0.20	....	....	....	0.60	....	....	....	0.05	....	....	....
26	0.16	....	0.52	0.30	....	1.90	....	....	0.01	....	....	....
27	0.81	....	0.77	0.79	....	....	....	0.12	....	....	0.10	....
28	0.05	....	....	2.87	....	1.28	0.02	....	....	....	....	....
29	....	——	....	0.64	....	....	....	0.56	....	....	....	....
30	0.01	——	0.04	1.27	1.07	....	....	....	....	....	....	....
31	....	——	....	——	....	——	....	....	——	0.32	——	0.08
Monthly Totals	2.44	2.28	2.59	12.94	3.49	8.71	4.32	2.02	1.96	3.60	6.61	1.43

Total yearly rainfall: 52.39 Inches

Appendix 1 (continued)

Annual Summary, 1995, Salem Weather Observation Station

Dent County, SE 1/4 NE 1/4 SEC. 24, T. 34 N., R. 6 W.
37° 38' 01" north latitude, 91° 32' 10" west longitude
Land surface elevation: 1205 feet above mean sea level
Weather observer: National Forest Service, Mark Twain National Forest
Installation operated by: National Weather Service
Type of installation: NWS recording rain gage
Station installed in 1899, 96 years of data

DAILY PRECIPITATION (INCHES) FOR CALENDAR YEAR 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.06	....	....	0.01	1.37	....	....	....	0.48	....	0.24	....
2	....	....	0.05	....	0.01	1.15	....	0.01	....	....	....	....
3	....	0.25	0.03	0.09	0.18	....	0.80	0.52	1.61	....	....	....
4	....	0.05	....	0.03	0.17	....	0.20	....	0.68	....	....	....
5	....	....	0.01	....	0.08	....	0.15	....	....	....	0.02	....
6	0.36	....	....	....	0.07	0.05	0.65	....	....	....	....	....
7	0.11	0.02	3.35	....	0.11	....	....	0.01	0.09	....	0.04	....
8	....	....	....	....	1.04	0.22	0.62	0.01	0.02	....	....	0.23
9	....	....	....	....	0.01	0.39	....	....	....	....	....	0.01
10	....	....	....	....	0.01	1.68	....	0.19	....	....	0.01	....
11	0.01	....	....	1.38	....	0.13	....	....	....	....	1.28	....
12	....	....	....	0.03	....	....	....	....	....	....	....	....
13	1.21	....	....	....	....	....	....	....	0.20	....	0.12	....
14	1.05	0.02	....	....	....	....	....	....	....	0.11	....	....
15	....	0.27	....	....	....	....	....	....	....	....	0.13	0.27
16	....	0.05	....	....	0.16	....	....	....	0.29	....	....	0.31
17	....	....	....	....	0.20	....	....	....	....	....	....	0.04
18	0.06	....	....	0.20	1.04	....	....	....	....	....	....	0.75
19	1.04	....	....	....	....	....	....	....	....	....	....	2.00
20	0.07	....	0.10	1.23	....	....	0.03	....	0.59	0.65	....	....
21	....	....	....	....	0.01	....	....	....	0.06	....	....	....
22	....	....	....	0.21	....	....	0.01	....	0.03	....	....	....
23	....	....	....	0.69	....	....	0.25	....	....	....	....	0.03
24	....	....	....	0.05	0.19	....	0.41	....	....	0.01	....	....
25	....	....	....	....	1.53	0.67	0.30	....	....	....	....	....
26	....	....	0.05	....	0.06	0.96	0.12	....	....	....	....	....
27	0.17	1.09	0.34	0.13	0.71	0.24	....	....	....	0.91	....	....
28	....	....	....	....	0.87	....	....	....	....	....	....	....
29	....	——	....	0.74	....	0.59	....	....	....	....	....	....
30	....	——	....	0.05	....	....	....	....	....	0.33	....	0.13
31	....	——	....	——	....	——	....	....	——	0.10	——	0.02
Monthly Totals	4.14	1.75	3.93	4.84	7.82	6.08	3.54	0.74	4.05	2.11	1.84	3.79

Total yearly rainfall: 44.63 inches

Back Cover:
Arch Houston and Ora Beckman ford Maramec Spring branch below the grist mill. Date and photographer unknown. Photo courtesy of the Lucy Wortham James Memorial Library and the James Foundation.

MISSOURI DEPARTMENT OF
NATURAL RESOURCES
Division of Geology and Land Survey
P.O. Box 250, Rolla, MO 65402-0250
(573) 368-2100